DEVELOPMENT OF A PROJECT COMPLEXITY ASSESSMENT METHOD FOR ENERGY MEGAPROJECTS

Ehsan Kian Manesh Rad

Submitted for the degree of Doctor of Philosophy

Heriot-Watt University

School of Energy, Geoscience, Infrastructures and Society

February 2016

ABSTRACT

Megaprojects are characterised by their large-scale capital expenditure, long duration and significant levels of technical and process complexity. Empirical data show that megaprojects in the energy sector experience alarming rates of failure, such as cost overruns, delays in completion and production shortfalls. One of the main causes of failure is their high level of complexity and the absence of effective tools to assess and manage it. Project complexity has received increasing attention in recent years, both in academia and the industry. However, there is still a lack of consensus on a clear definition for 'project complexity' or a comprehensive list of complexity indicators, specifically for energy megaprojects. Furthermore, there is also a lack of a widely accepted assessment method to measure project complexity in a quantitative manner.

This study is carried out in response to these problems. First, it develops a taxonomy of project complexity indicators on the basis of a comprehensive review and synthesis of existing literature. It includes 51 internal and external Project Complexity Indicators (PCIs) in a logical hierarchical structure; these indicators specify the aspects that need to be measured when assessing project complexity. Second, weights for all indicators are established through an integrated Delphi-AHP method, with the participation of 20 international experts. Finally, the study specifies Numerical Scoring Criteria (NSCs) for all indicators based on a synthesis of existing knowledge about megaprojects. The criteria specify the scoring thresholds, on a 1-5 scale, for each indicator. These three components constitute a new Project Complexity Assessment (PCA) method, which is implemented as a spreadsheet PCA tool. The developed tool allows a project team to assess and score their project in each of the PCIs against the defined criteria. It then calculates two separate complexity indices for internal and external factors; the results indicate the complexity level of the project. Complexity profiles are also produced to illustrate the complexity scores of different categories of PCIs.

The PCA method is tested using an energy megaproject case study. The results demonstrate not only that the tool can help a project team understand the complexity of their project, but also it can help the team to develop appropriate complexity management strategies by comparing the assessment results of different projects.

DEDICATION

This Thesis is dedicated to my Parents, Mehdi and Shahla.

ACKNOWLEDGMENT

I would like to extend my profound thanks to my supervisor Professor Ming Sun for his excellent expertise and mentoring during my study. His gifted personality, immense knowledge, motivation and belief have helped me to accomplish this task. The memory he has implanted in me will remain forever.

I also offer my sincere gratitude to my second supervisor, Dr. Frédéric Bosché, for his valuable advice, encouragement and support during my study. Without support from both supervisors, this thesis would not have evolved as it has.

I would like to thank all the respondents to the questionnaires, interviews and case study for their valuable contribution, time, and the effort they spent, which made this study possible.

I would like to thank my parents, Mehdi and Shahla, for their love and dedications which leaves me speechless, their love encouraged me to reach the end of this hard journey. A special "thank you" also goes to all my family for supporting me with their best wishes.

Every moment of my life during this period I have been engaged with ups and downs; however, being with lovely friends has made it enjoyable. I especially thank Harijanto, Jennifer, Francesca, Giuseppe, Arman, Parastoo, Majid, Afrooz, Morteza, Mojtaba and Babak.

Finally, I offer this quote from Carlos Castenda:

"Look at every path closely and deliberately, then ask ourselves this crucial question: Does this path have a heart? If it does, then the path is good. If it doesn't, it is of no use"

ACADEMIC REGISTRY

Research Thesis Submission

Name*:*	EHSAN KIAN MANESH RAD		
School/PGI:	EGIS		
Version: *(i.e. First, Resubmission, Final)*	FINAL	Degree Sought (Award **and** Subject area)	PhD in Construction

Declaration

In accordance with the appropriate regulations I hereby submit my thesis and I declare that:

1) the thesis embodies the results of my own work and has been composed by myself
2) where appropriate, I have made acknowledgement of the work of others and have made reference to work carried out in collaboration with other persons
3) the thesis is the correct version of the thesis for submission and is the same version as any electronic versions submitted*.
4) my thesis for the award referred to, deposited in the Heriot-Watt University Library, should be made available for loan or photocopying and be available via the Institutional Repository, subject to such conditions as the Librarian may require
5) I understand that as a student of the University I am required to abide by the Regulations of the University and to conform to its discipline.

* *Please note that it is the responsibility of the candidate to ensure that the correct version of the thesis is submitted.*

Signature of Candidate*:*		Date:	

Submission

Submitted By *(name in capitals):*	
Signature of Individual Submitting:	
Date Submitted:	

For Completion in the Student Service Centre (SSC)

Received in the SSC by *(name in capitals):*			
Chapter 1Method of Submission *(Handed in to SSC; posted through internal/external mail):*			
Chapter 2*E-thesis Submitted* *(**mandatory for final theses)***			
Signature:		Date:	

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF PUBLICATIONS

Kian Manesh Rad, E. & Sun, M., 2014. Taxonomy of Project Complexity Indicators in Energy Megaprojects. In *People, Buildings and Environment an international scientific conference, Czech Republic*. Awarded as the best doctoral contribution.

Kian Manesh Rad, E., Sun, M., Bosché, F., 2015. A Consistency-Checking Consensus-Building Method to Assess Complexity of Energy Megaprojects. In *IPMA 29th World Congress, Panama*. Selected paper for *Procedia - Social and Behavioral Sciences, 2016.*

Kian Manesh Rad, E., Sun, M., Bosché, F., 2015. A Complexity Assessment Method for Megaprojects in the Energy Sector. In *International Journal of Project Management. (Under review)*

LIST OF ABBREVIATIONS

AHP	Analytic hierarchy process
ANP	Analytic network process
AON	Activities on node
BTC	Baku-Tbilisi-Ceyhan
CBA	Cost-benefit analysis
CC	Cordial consistency
CI	Complexity index
CNC	Coefficient of network complexity
COST	Cooperation in science and technology
CPM	Complex project management
CR	Consistency ratio
DMO	Defence material organisation
EEEM	Energy engineering environment management and business
ELECTRE	Elimination and choice translating reality
EU	European Union
EV	Eigen value vector
EY	Ernst & Young
FANP	Fuzzy analytic network process
FEL	Front-End loading
FHA	Federal highway administration
GAPPS	Global alliance for project performance standards
GCI	Geometric consistency index
GDM	Group decision making
GDP	Gross domestic products
GM	Geometric mean
IEA	International energy agency
IPA	Independent project analysis
IPMA	International project management association
IPME	International program in the management of engineering
KRNW	Knowledge resource nomination worksheet
LRMS	Logarithmic residual mean square
MPA	Major project association
NAO	National audit office

NGT	Nominal group technique
NIS	Negative ideal solution
NSC	Numerical scoring criterion
OC	Ordinal consistency
OPT	Operational
PCA	Project complexity assessment
PCI	Project complexity indicator
PCM	Pair-wise comparison matrix
PCRA	Project complexity and risk assessment
PIS	Positive ideal solution
PMI	Project management institute
PRINCE2	Project in controlled environment
PROMETHEE	Performance ranking organisation for enrichment evaluation
QA	Quality assurance
QC	Quality control
RI	Random index
TOE	Technology, organisation and environment
TOPSIS	technique for order performance to ideal solution
USD	US Dollar
WoS	Web of science

Chapter 1 Introduction

1.1 Introduction

This chapter presents an overview of this PhD research. It is organised in the following order: background of the research problems; definition of the research scope; research aims and objectives; research methodology; and finally, the structure of the thesis.

1.2 Background and Problem

Energy is one of the most essential resources needed in modern society. With an average annual growth rate of 1.6 percent in demand, it is estimated that the world's energy need will be more than 50% higher in 2030 than in 2007 (Birol 2006). To satisfy this need, the first decade of the twenty-first century has seen the construction of very large and complex energy infrastructures (Merrow 2011). These are often called *megaprojects*, which are commonly defined as projects with a capital investment of at least one billion U.S. dollars (Merrow 2011; Flyvbjerg et al. 2003; DTIOG 2001). Beside the scale of their price tag, megaprojects are also typically characterised as being risky and complex, with high uncertainty and social impact, as well as engaging many stakeholders (Kardes et al. 2013). Typical energy megaprojects include oil and natural gas extraction fields and refineries, large hydroelectric, nuclear or other types of power stations, and renewable energy projects such as wind and solar farms.

Unfortunately, these megaprojects are experiencing alarming rates of failure in meeting their business goals, their capital budgets, or their delivery schedules (Merrow 2011; Cantarelli et al. 2012). Cantarelli et al. (2012) investigated 806 capital projects worldwide (energy project, transportation projects etc.) and found an average cost overrun of 35.5%. A report on the energy sector by the Independent Project Analysis (IPA), based on a study of 318 projects across the world, has also demonstrated problematic performance of energy megaprojects (Merrow 2012). Only 22% of these projects could reasonably be considered successful, with the other 78% as disappointing. Those failed projects have experienced 33% real cost overruns, 30% execution schedule slips, and more importantly, 64% serious production shortfalls in the first 2 years of operation. Yet, despite such failures, megaprojects continue to grow in size and scope, especially energy megaprojects (Thaler 2014).

A report by the International Energy Agency highlighted that "easily accessible" energy resources have already been extracted and the new fields to be exploited are located in more difficult areas (e.g. deep water or remote fields). As a result, the complexity of megaprojects is set to increase (Internationa Energy Agency 2006). Flyvbjerg et al. (2003) and Merrow (2011) suggested *complexity* as one of the main causes of megaproject failures, along with information distortion, cost, catastrophic political and environmental conditions and conflicting stakeholders. Sovacool & Cooper (2013) identified five different elements which cause failures in energy megaprojects; one of them being complexity and the others being social, technological, political and economic. Procaccini et al. (2012) blamed the project teams' inability to adequately determine and manage a project's complexity as the largest risk to project delivery in the field of capital energy megaprojects.

With the increase in recognition of project complexity as one of the most essential obstacles to successful project delivery, particularly for megaprojects, the last decade has seen an increase in studies on this topic. However, so far there is still a lack of consensus on the meaning of the term "project complexity", and on the best methods to assess and manage it. Vague terminology is highlighted by Williams, 2002, *"While many project managers use the term 'a complex project', there is no clear definition of what is meant. There is a general acceptance; however that it means something more than a 'big' project".* A group of researchers has explicitly focused on explaining project complexity by using a dictionary definition: "consisting of many interconnected parts", comprising physical factors and interdependencies, and also by taking 'uncertainty' as an additional factor into account (Baccarini 1996; Williams 2002; Geraldi & Adlbrecht 2007). Others have attempted to clarify the topic by using complexity theory and its relation to project context (Remington & Pollack 2007; Cooke-Davies et al. 2007). Among these efforts, a more specific realisation of project complexity is introduced by Williams (1999), who explained that a project's complexity increases as a result of swift changes in environment, enlarged product complexity and increased project time pressure. More recent research explained project complexity by employing a number of complexity indicators; but the categorisation of these indicators has not been universally agreed.

According to Sovacool & Cooper (2013), effective recognition and determination of complexity in a project can aid project managers to identify and assess potential causes of failure, and to adopt a management approach designed to attain the projected objectives. Little et al. (1998), Williams (2002) and Vidal et al. (2011) have highlighted the importance of objective and quantitative evaluation of complexity, and the need for any practice driven complexity assessment method to entail objective measurement. However, previous studies are mostly devoted to the theoretical aspects of project complexity (Maylor et al. 2008; Kardes et al. 2013). No tool is yet available to accurately quantify complexity of megaprojects in general and of those in the energy sector in particular.

In order to confront the project complexity problem in practice, a preliminary investigation was conducted through semi-structured interviews with six professional experts from the energy sector. The results highlighted a lack of consensus on the definition of project complexity and of methods to measure it. There is a clear desire for an objective method of evaluating project complexity in practice.

1.3 Research scope

To tackle such a broad topic as project complexity of megaprojects, it is necessary to narrow down the investigation. First, the study will clarify what constitutes a megaproject; detailed discussion is presented in Chapter 2. Then, the scope of research is further narrowed down to energy megaprojects, such as gas and oil explorations, as well as renewable energy developments. The rationale for this choice is explained in the discussion of the previous section. The main focus of this study is on understanding complexity of energy megaprojects and developing an assessment method to measure that complexity. Complexity management is beyond the scope of this current research initiative.

1.4 Aim and objectives

The aim of this study is to:

Develop a comprehensive and robust project complexity assessment method for energy megaprojects.

This new project complexity assessment (PCA) method should help to enhance the quality of decision making processes for practitioners and lead to more successful management of megaprojects in the energy sector.

In order to develop such a method, this research needs to pursue answers to the following questions:

1. What are the key aspects that characterise project complexity for energy megaprojects?

2. How much does each of these aspects contribute to the overall project complexity?

3. How can these project complexity aspects be measured quantitatively?

To achieve the defined aim and to answer the above questions, the following objectives are identified:

1 To identify the perceived gaps between theory and practice within existing methods for assessment of project complexity, with a specific focus on energy megaprojects;

2 To identify contributing project complexity indicators (PCIs) and establish a logical standard categorisation for them;

3 To establish the relative importance and weight of each project complexity indicator;

4 To define numerical scoring criteria for all project complexity indicators;

5 To evaluate the developed project complexity assessment method.

1.5 Research Methodology

This research adopts both deductive and inductive approaches, with a mixture of qualitative and quantitative research methods. The research process consists of five stages; each of these stages addresses one of the above research objectives, as depicted in Figure 1-1:

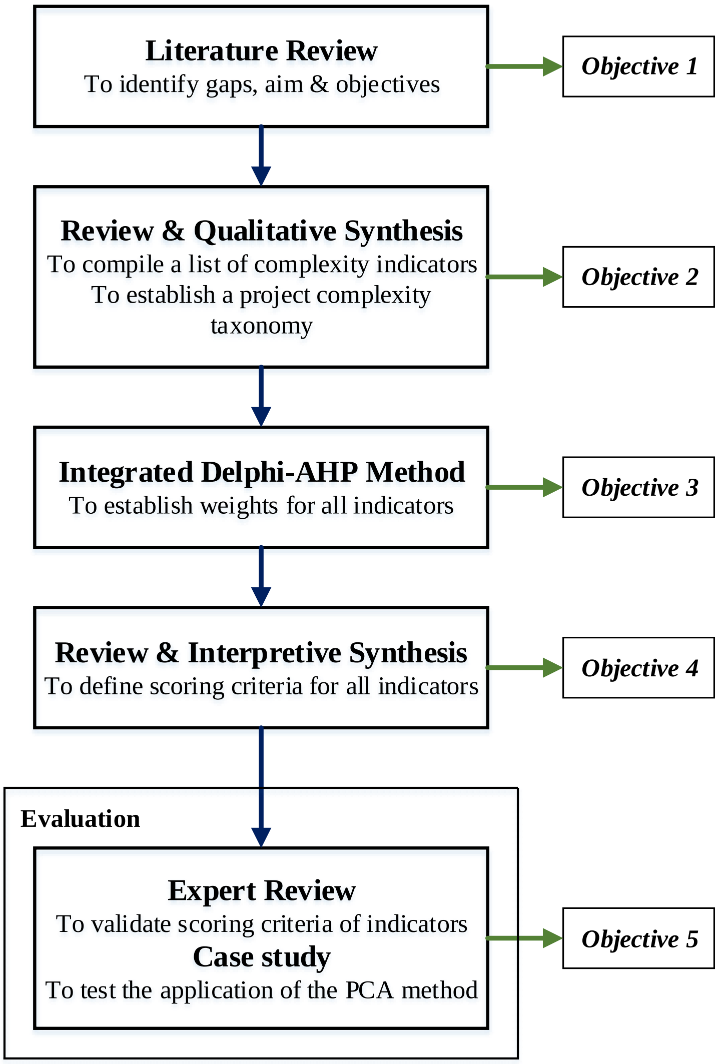


Figure 1-1: The research process

(1) The literature review on project complexity and megaprojects establishes state-of-the-art knowledge and identifies existing research gaps in relation to project complexity and assessment methods. In addition, a series of interviews with professional experts is undertaken to gain an insight into existing challenges and needs in practice. Details are presented in Chapters 2 and 3.

(2) Compiling a list of PCIs is achieved through a comprehensive literature review and synthesis. Firstly, a systematic review is done on project complexity and megaproject, based on the approach suggested by Geraldi et al. (2011). To ensure the quality and relevance of publications, only journal articles, books, published proceedings, and authoritative reports are considered. In total 50 relevant information sources have been identified, including studies on megaprojects as well as general projects. Secondly, complexity indicators are

identified in those publications and recorded with a brief definition. Altogether 110 relevant indicators were identified. The next task is to consolidate these indicators into a taxonomy of PCIs. This is carried out in two steps: (1) the identified indicators are compared and merged when similar. This step reduces the number of indicators from 110 to 51; (2) the remaining 51 indicators are categorised into semantic groups to develop a logical hierarchical structure. The outcome is a taxonomy of PCIs for megaprojects. The process and result of the establishment of the PCI taxonomy are detailed in Chapter 5.

(3) The third phase uses an integrated Delphi-AHP method. International experts with high familiarity and knowledge within the energy sector and megaprojects are selected and two panels of 20 experts are set up, comprising of 10 academics and 10 industry practitioners. AHP matrices are used to establish the comparative ranking weightings for complexity indicators in the taxonomy. Two rounds of the Delphi method are carried out to gain an acceptable level of consensus amongst the experts. The Delphi-AHP process is presented in Chapter 6.

(4) Scoring criteria are essential to the practical quantification of project complexity, yet this aspect has been frequently neglected in existing research. To fill this gap, numerical scoring criteria for all identified indicators are defined based on comprehensive literature synthesis (Chapter 7).

(5) The outcomes from the previous three phases define the principle and algorithms of the new PCA method. The final phase is to implement the PCA method as a spreadsheet tool; then test it through a case study project (Chapter 8).

A detailed discussion of the research methodology is presented in Chapter 4.

1.6 Structure of the thesis

This thesis contains nine chapters and is organised as follows:

Chapter 1 provides an introduction to this study.

Chapter 2 presents a literature review focusing on project complexity and megaprojects. It highlights problems and characteristics of megaproject, and the current understanding of project complexity.

Chapter 3 presents a literature review of existing methods and tools for project complexity assessment (PCA). A critical review explores existing assessment methods in research and practice. The chapter also gives details of interviews conducted with professionals in the energy sector. It highlights limitations and gaps in both literature and practice.

Chapter 4 discusses the research methodology, including philosophy, approach, and methods for collecting data. It describes the research process relating to the five main stages and justifies the procedure and methods used.

Chapter 5 presents the process of identifying project complexity indicators (PCIs) and establishing a taxonomy.

Chapter 6 describes the use of an integrated Delphi-AHP method to elicit the rankings and consolidated weights of the PCIs.

Chapter 7 presents the specification of numerical scoring criteria for all PCIs on the basis of a review of the key literature and interpretive synthesis. The scoring criteria are evaluated through expert reviews.

Chapter 8 describes the evaluation and testing of the developed PCA method through a case study. The purpose is to demonstrate its application in practice and gather feedback from professionals.

Chapter 9 first summarises the research results and demonstrates how, and to what extent, the research objectives are achieved. Then it highlights the contribution of this study from both academic and practice perspectives. Finally, the limitations of this research and recommendations for future research are discussed.

Chapter 2 Megaprojects and Project Complexity

2.1 Introduction

This chapter reviews project complexity in the context of megaprojects. It is divided into two main sections. Section 2.2 examines key aspects of megaprojects, such as definition, characteristics and existing problems. Section 2.3 focuses on project complexity, including complexity aspects and indicators for projects in general, as well as megaprojects in particular.

2.2 Megaprojects

2.2.1 *Definition*

Definitions of megaprojects vary based on the view points of the authors who proposed them. The U.S. Department of Transportation and the U.S. Federal Highway Administration (FHA) brought a detailed definition of megaprojects as "…major infrastructure projects that cost more than 1 billion USD, or projects of a significant cost that attract a high level of public attention or political interest because of substantial direct and indirect impacts on the community, environment, and state budgets" (Capka 2004; DTIOG 2001). *Major project* or *major programme* is another term that is commonly used to refer to large projects in several countries, such as the United Kingdom. The Major Projects Association (MPA) defines major projects as "those which require knowledge, skills or resources that exceed what is readily or conventionally available to the key participant" (Major Projects Association 2014).

Miller & Lessard (2001) investigated sixty large scale engineering projects. In their sample, the average capital budget was US$ 985 million and the average duration was six and a half years, which indicate high capital budget and long duration. The project cost threshold of US$1 billion is defined by Merrow (2011) as the key measure for defining a megaproject and is accepted and used by some other researchers (Flyvbjerg et al. 2003). In the European Union (EU), the International Project Management Association (IPMA 2013) defined a cost threshold of 100 million euros for megaprojects across all industries. Another recent definition is suggested by European Megaprojects Research Action which considered megaprojects as large-scale investment projects typically costing more than EUR 0.5 billion (Locatelli et al. 2014). Although, the US$1 billion threshold has been defined and used arbitrarily (Merrow

2011), it has been argued that it can only be adopted for developed countries because the capital size of largest projects are much lower in developing countries, with their far lower gross domestic products (GDPs). Thus, Flyvbjerg (2009) proposed a cost-GDP ratio to determine megaproject cost threshold. He suggested that most megaproject cost-GDP ratios are between 0.01 and 0.02%. This study adopts this threshold definition of 0.01% of GDP as a criterion for megaprojects.

Beside total capital budget, megaprojects can be further distinguished by their other characteristics. Grün (2004) described megaprojects using four aspects: (1) singularity, (2) complexity, (3) goal-focused (technical, economic, time), and (4) the nature and the number of stakeholders. Hassan et al. (1999), in addition to their high capital budgets, specified large scale engineering projects based on another four features: (1) long duration and programme urgency, (2) technologically and logistically difficult, (3) demanding multidisciplinary inputs from many stakeholders, and (4) leading to a "virtual enterprise" for the execution of the project.

Megaprojects are commonly characterised as risky, complex, with high uncertainty and interdependence and involving social impacts, as well as engaging many stakeholders. They often exhibit distinctive characteristics of: political delicacy (Kardes et al. 2013; Locatelli et al. 2014); public attention (van Marrewijk et al. 2008; Brooks 2013); durations of between four years and a decade or sometimes more, including design, execution and delivery (Merrow 2011; Fiori & Kovaka 2005); high levels of complexity (Remington & Pollack 2007; Priemus, Flyvbjerg & van Wee 2008; Flyvbjerg et al. 2003; Merrow 2011; Brockmann & Girmscheid 2007); high risk (Flyvbjerg et al. 2003; Flyvbjerg 2009); uncertainty (Geraldi et al. 2011; Bosch-Rekveldt et al. 2011); involving domestic and multi-national stakeholders with a variety of cultural differences, backgrounds, political systems, and languages (Shore & Cross 2005; Kardes et al. 2013); new technologies (Cicmil et al. 2009; Grün 2004; Priemus, Flyvbjerg & Wee 2008) and unreliability or difficulty to access valid information (Flyvbjerg et al. 2003; Flyvbjerg 2009; Locatelli et al. 2014). These attributes, in turn, often have an adverse impact on the performance of a megaproject's delivery, and on many occasions have caused drastic project failures. Therefore, it is essential to have a better understanding of the degree of impact of these factors, before appropriate mitigating measures can be adopted. Suitable assessment methods are required in order to gain an accurate understanding of the issues involved in successful, or otherwise, project delivery.

The International Energy Agency (IEA) estimated that the total capital investment of the energy industry worldwide will be nearly US$38 trillion for energy projects until 2035, and at least 50% of this investment will be on large capital projects to maintain existing assets, such as pipelines and grids or building new infrastructures. The increasing importance of energy megaprojects, together with their existing high failure rate, underline the importance of this particular research.

2.2.2 *Characteristics of megaprojects*

At least six prominent attributes associated with megaprojects are commonly stated: 1. Extreme complexity; 2. Engaging many resources; 3. Long project schedule; 4. Engaging many stakeholders; 5. Technology; 6. Social and political significance.

Extreme complexity

- The complexity of megaprojects is manifested in different aspects. Capka (2004) suggested that complexity increases as a result of lack of coordination among stakeholders, with their conflicting aims and interests. However, the problem does not only arise from conflicts as Davies & Brady (2000), Williams (2002), Flyvbjerg et al. (2003), Pryke & Smyth (2006), van Marrewijk et al. (2008), Hertogh et al. (2008), Vidal et al. (2011) and Merrow (2011) all highlighted that a significant number of project stakeholders, including contractors, governments, private sector, suppliers and financiers, will contribute to increased complexity. Complexity increases because each stakeholder has their own interests, which are not always aligned with those of others. Capka (2004) also identified changes during the project, such as changes in laws and regulations, the political environment and the economy, as other sources of complexity. In addition, megaprojects usually comprise high numbers of different interconnected activities, which constitute another factor contributing to increases in the complexity of a project or projects (Kardes et al. 2013). Megaprojects are commonly engineering-driven, so it is likely they will face technological challenges. Some entail cutting-edge technologies, which are not fully acquired at the time of project execution. As a result, it increases the complexity of the planning and operating of projects (Priemus et al. 2008).

Engaging many resources

- Megaprojects are characterised as consuming large amounts of resources including equipment, labour, capital, material and facilities. The workforce often totals thousands, and the skilfulness of the workforce has a significant impact on a megaproject's performance (Fayek et al. 2011). Many megaprojects, such as those involving offshore energy, are constructed in very remote geographical areas where it is extremely challenging to provide competent skilled labour (Merrow 2011; Sovacool & Cooper 2013; Fiori & Kovaka 2005), as well as all necessary equipment.

Long project duration

- Another significant characteristic of megaprojects is their very long duration. It may take several years for the final delivery of the project to occur and to achieve the expected production goals (Haynes 2005; Merrow 2011). Sovacool & Cooper (2013) remarked that energy megaprojects typically have durations of at least four years. This long duration challenges project participants and managers, as it increases the likelihood of changes both internally and externally.

Engaging many stakeholders

- Megaprojects often aim to deliver benefits to a wide range of stakeholders. With many participants engaged in projects, accommodating each participant's requirements is a very challenging task (Flyvbjerg et al. 2003; Flyvbjerg 2009; Feldman 1985). Diverse interests between public and private, or between supply and demand stakeholders, or difficulties in managing different demands of financiers, clients, contractors, local authorities, environmentalists and media are examples of such challenges (Xia & Chan 2012).

Technology

- Technological challenges are often a distinctive attribute of megaprojects. The need for new technologies in some megaprojects hinders timely progress of those projects due to their complexity and lack of useful past experience within the project team (Whitty & Maylor 2009). Even employing routine and familiar technologies may not guarantee the success of a megaproject. In a study of a portfolio of oil & gas megaprojects, Ernst & Young (EY 2014) showed that around 60% of failures occurred in projects involving routine and highly experienced familiar technologies. Feldman (1985) associated the causes of failures of routine technologies in major and large engineering megaprojects to their dependency on matters outside the project.

Social and political significance

- Megaprojects often raise substantial public interest (Flyvbjerg 2009). Therefore, their success is not only critical to their sponsors, but also to the general public (Shore & Cross 2005). This places megaprojects at the centre of attention of politicians and those projects can have significant impact, either positive or negative, on their electoral fortune (Hall 1982). Therefore, megaprojects, from politicians' and the public's perception, are commonly seen as significant dilemmas. If attitudes turn negative, the shift can lead to changes in policies and regulations and consequently hinder further developments of megaprojects (Flyvbjerg et al. 2003). Moreover, the negative impact of failures may be trans-national, affecting the economy, and even the natural environment, for several generations (Chatterji 1997; Cantarelli et al. 2012).

2.2.3 *Existing Problems of megaprojects*

Cost overrun

Cost overrun is considered the most frequent and serious failure of megaprojects (Merrow 2011; Flyvbjerg et al. 2003). Flyvbjerg et al. (2003) found that cost overruns exist in almost all types of megaprojects across both developed and developing countries. In another study, Cantarelli et al. (2012) showed an average cost overrun of

35.5% in 806 major construction projects worldwide. In fact, numerous high-profile megaprojects around the world have resulted in significant cost overruns (*Table 2-1*).

Table 2-1: Some well-known megaprojects with significant cost overrun

Megaproject and location	Sector	Cost overrun %
Baku-Tbilisi-Ceyhan (BTC) Pipeline, Azerbaijan, Georgia, turkey (Sovacool & Cooper 2013)	Energy	85
Flamanville 3 Nuclear Power Plant, France (Locatelli & Mancini 2013)	Energy	81
London Olympic, UK (Flyvbjerg & Stewart 2012)	Construction	101
Opera house Sydney, Australia (Flyvbjerg et al. 2003)	Construction	1600
Boeing 787 Dreamliner plane, USA (Kardes et al. 2013)	Transport	76
Channel tunnel, UK and France Transport (Flyvbjerg et al. 2003)	Transport	80

In the energy sector, Ernst and Young (EY 2014) conducted a comprehensive study to highlight the challenges associated with the delivery of megaprojects in the oil and gas industry. The study investigated 365 global megaprojects (with capital investment above US$1b) with a combined capital investment of approximately US$2.6 trillion. The results highlighted poor performance, with 65% of projects experiencing cost overruns and the average project completion cost estimated to be 59% above the planned estimate. Accenture's Innovation Center for Energy and Utilities (2012) conducted research that surveyed 61 energy sector executives from 21 countries, who were responsible for capital megaprojects of at least US$1 billion. The results highlighted cost overruns could reach 29%, which translates into a US$11 trillion overrun based on the US$38 trillion global investment forecast. The study states that "the increasing size and complexity of today's major projects has boosted the scale of challenges for energy companies globally" (Procaccini et al. 2012). It cites technical capabilities, regulatory requirements and workforce/skills availability as the key challenges that should be addressed.

Ernst & Young (EY 2014) suggested increased complexity is largely to blame for failures of megaproject, with 65% of failures due to softer aspects of projects, such as people, organisation and governance. 21% of failures were due to management processes and contracting and procurement issues, and the remaining 14% of failures were due to external factors such as political and environment-related matters. Changes during a project are another significant cause of cost overruns in megaprojects. The cause of change may be from utilising a new technology, a lack of sponsor familiarity with the area, downward labour productivity, or fixed-price contracts in projects (Flyvbjerg 2009; Greiman 2013).

Delays

Project delays are another main problem experienced by many megaprojects. A study by the International Program in the Management of Engineering (IPME) ranked 'schedule slip' as the highest risk to the successful delivery of large engineering projects worldwide (Miller & Lessard 2001). The World Bank (2009) reported that schedule overrun varied from between 50% - 80% for a group of 233 capital projects between 1999 -2005. In the United Kingdom, the National Audit Office (NAO) reported that 70% of the government's major projects were delivered late (National Audit Office 2012). And, a recent investigation of a large portfolio of capital energy megaprojects worldwide revealed an alarming rate of 74% of projects experienced schedule delays (EY 2014).

Although schedule slips appear to be an embedded issue in all types of projects, determining the main causes and mitigating them before they lead to failures are much more effective options than undertaking subsequent actions. Project schedules are very sensitive to intensity of engineering tasks. In the case of megaprojects, poor-quality engineering, together with innovative or complex systems often cause the late delivery of a project (Merrow 2011). Some of the large schedule slips can also be caused by external political forces (Sovacool & Cooper 2013). For instance, when the Russian government withdrew the construction permit of Sakhalin II oil and gas development project while the project was under construction, because of new political and economic conditions, it caused huge schedule delays.

Production shortfalls

Production shortfalls are a particularly significant aspect of failure in megaprojects. In other words, the production output of the completed facility is below the expected level. A report on the energy sector by the Independent Project Analysis (IPA), involving 318 megaprojects across the world over a 20-year period, highlighted that 78% of projects had suffered from an average of 64% production shortfalls in the first 2 years of operation (Merrow 2011). An updated IPA report, for the period 2002-2010, reported an increase in performance of energy megaprojects in terms of production and schedule delivery; however almost half of the projects still had significant operability and production problems. The most common cause of these problems was associated with increased complexity of project due to the inaccuracy of initial forecasts, and unreliability and/or inaccessibility of required information (Flyvbjerg 2014).

When megaprojects fail, the results are rarely publicised because they are damaging to the company's reputation. Significant cost overruns, or slips in schedule and production shortfalls of past projects, damage the developer's capacity to obtain funds for future projects. Hence, companies tend to conceal detailed results or any analysis of the root-causes of failures. Such policies have led to a two-fold problem: firstly, experts and researchers cannot access reliable information to carry out practical studies; secondly, companies cannot benefit from the results of expert and academic research.

2.3 Project complexity

Complex project management initiates from complexity theory (Whitty & Maylor 2009); a theory that was developed by the Santa Fe Institute in the 1980s to solve complicated problems of natural science such as astronomy, biology, or in social science such as the economy. Implementation of complexity theory in project management science appeared in the late 1990s (Baccarini 1996; Williams 2002). The surge in scope, size and technological aspects of projects led to the emergence of increasing numbers of complex projects (Fiori & Kovaka 2005; Remington & Pollack 2007).

There are two main scientific streams on complexity, namely descriptive and perceived complexity (Vidal & Marle 2008). *Descriptive complexity* reflects complexity as an inherent attribute of a system; it suggests that the level of complexity can be quantitatively evaluated and measured. This entails a process that requires the identification of a structured set of measurable aspects, or indicators, of complexity. An early work pursuing a descriptive approach is that of Baccarini (1996), who categorises project complexity into technological and organisational complexity.

Alternatively, *perceived complexity* results from a particular perception of a situation (of complexity) made by an observer (Schlindwein & Ison 2004). Indeed, it can be argued that, in practice, a project manager cannot recognise the whole reality and complexity of the project, and thus s/he only achieves a perceived and subjective, rather than a more objective, understanding of complexity (Fioretti & Visser 2004). Different people linked to a project have different points of views because of their positions within the organisation or their different backgrounds and experience. For example, a young member in a project's team does not necessarily see aspects of complexity that an experienced member sees; or a beginner may observe and consider something to be complex that an experienced may see it only as a relatively simple challenge. Also an individual's personality can impact on how complexity is perceived; yielding differences in views between a specialist and a generalist (Remington et al. 2009). As a result, different people will have different perceptions about the complexity of the same project; the same people may even have different perceptions about the complexity of the same project at different times.

This research follows a descriptive approach and focuses on the objectivity aspect of project complexity. The remaining part of this chapter presents a review of the literature dealing with project complexity and complexity indicators.

2.3.1 *Definition*

There is a lack of consensus within the literature on what project complexity exactly is. As Sinha et al. (2001) highlighted, "there is no single concept of complexity that can adequately capture our intuitive notion of what the word ought to mean". Complexity can be comprehended in different ways, not only in different fields, but also within the same field (Morel & Ramanujam 1999). Lloyd (2006) provided 32 definitions of complexity in his book 'Programming the Universe', but he rejected the idea of providing an explicit definition:

"I can't define it for you, but I know it when I see it."

Likewise, Paterson (2006) presented an ambivalent definition and formulated 'complex' as:

"complex = not simple and never fully knowable. Just too many variables interact".

Given the absence of an explicit definition of 'complexity', it can be characterised by its large number of interacting parts; the science of complexity is the study of these interactions (Weaver, 1948). Complex systems are defined as those that entail a large number of intensely interacting components (Simon 1962). Van Der Lei et al. (2010) considered a complex project as a complex system consisting of many actors that continuously cooperate with a physical/technical setting and evolving characters. These definitions, that are quite fitting to address aspects of project complexity for a descriptive approach, underline structural aspects of complexity. A holistic definition of project complexity should consider structural, dynamic and interactive components of any project (Whitty & Maylor 2009), as well as socially constructed entities (Cicmil et al. 2009).

The College of Complex Project Managers and Defence Materiel Organisation (DMO) of Australia identified some characteristics of complex projects, that distinguish them from characteristics of conventional projects (DMO 2006). According to them, complex projects are characterised by their level of disorder, instability, irregularity and randomness; a high degree of uncertainty on goals; and diverse stakeholders' views.

2.3.2 *Aspects of project complexity*

Despite the lack of an agreed definition of project complexity, many researchers have focused on characterising the complexity of a project. An early theoretical analysis of project complexity was offered by Baccarini (1996). He defined project complexity as technological and organisational complexity and proposed that project complexity "consists of many varied interrelated parts and can be operationalised in terms of differentiation and interdependency". He also added that complexity, as a project characteristic, differs from other project characteristics such as size and uncertainty. Turner & Cochrane (1993) argued that uncertainty of objectives and methods also leads to the complexity of a project.

Further to the work of Baccarini and Turner & Cochrane, Williams (1999) proposed that project complexity can be characterised by structural and uncertainty dimensions, as each comprises differentiation and interdependency aspects. Structural complexity includes ‘differentiation’ which interprets the number of hierarchical levels, number of formal organisational elements and diversity of tasks; ‘interdependency’ refers to the level of operational interdependencies between organisational units. Uncertainty involves ‘differentiation’ that interprets the uncertainty in goals, and uncertainty in elements of products; ‘interdependency’ translates to uncertainty of methods.

All projects are seeking to deliver a product or achieve a certain goal; so product complexity contributes to project complexity. Product complexity has multiple dimensions such as the level of customisation, the level of innovation, the number of sub-components, the level and variety of required skills and experience (Barlow 2000; Hobday et al. 2000).

The next aspect of project complexity emerged in 2005 with Williams proposing the concept of ‘pace’ as another applicable aspect. The three dimensions of pace, structural complexity and uncertainty were suggested by Dvir et al. (2006). The socio-political dimension of complexity was presented by Remington and Pollack (2007) and indirectly by Maylor et al. (2008). Geraldi & Adlbrecht (2007) offered three aspects of complexity as fact, faith and interaction. Complexity of faith is similar to uncertainty and implies new and innovative tasks; for instance the uncertainty of completing certain tasks. Complexity of fact relates to the fact that decisions may have to be made based upon incomplete information. The complexity of interaction merges at the interface among people and organisations, and covers aspects related to politics and multi-cultural variables. In addition, “tight time constraints”, schedules and urgency were also proposed as a time-centric aspect of project complexity (Shenhar & Dvir (2007).

Geraldi et al. (2011) suggested a framework of project complexity, building on previous works, and concluding structure, uncertainty, dynamics, pace and socio-politics to be the main aspects. Vidal et al. (2011) offered a two-dimension framework considering organisational and technological aspects of complexity. Each is further categorised into size, variety, interdependence and context dependence. Bosch-Rekveldt et al. (2011) carried out an extensive review of the literature and concluded that “environment” constitutes an additional aspect of complexity, forming with the other two a Technology, Organisation and Environment (TOE) framework.

The emergence of the aspects of project complexity is either built on previous work or new aspects. 'House of Project Complexity' conceptualised complexity in large infrastructure projects in technical and institutional complexity (Lessard et al. 2014). Dunović et al. (2014) added complexity of 'constraints' as a new aspect to the Baccarini/Williams aspects; the structural – uncertainty model. A study by Nguyen et al. (2015) identified six aspects for project complexity: socio-political, environmental, organisational, infrastructural, technological and scope. In another recent study, He et al. (2015) categorised complexity into technological, organisational, goal, environmental, and cultural.

Figure 2-1 summarises aspects of project complexity distilled from the literature. It depicts that at this stage, a consistent breakdown of project complexity is not possible. There is no unified understanding of these aspects. In addition, many of the aspects that have been proposed need to be understood in the context of a specific project sector, e.g., construction or transport. One of the tasks of this current study is to develop a detailed framework of aspects informing the complexity of energy megaprojects, by building on existing studies.

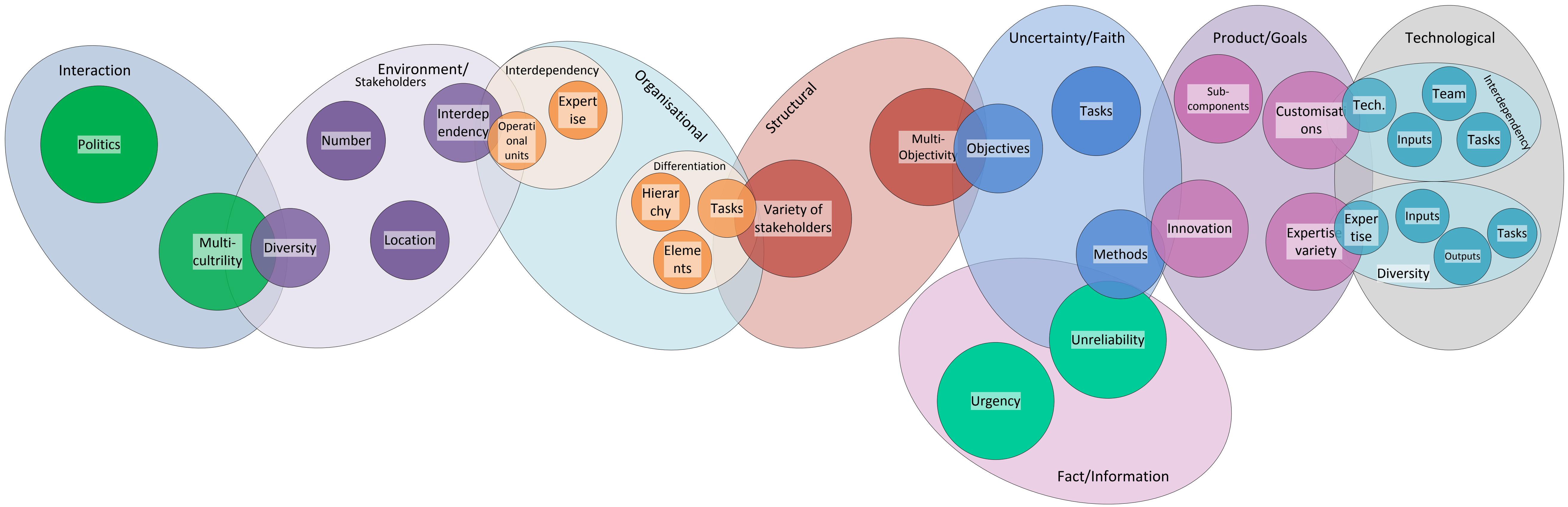


Figure 2-1: Distilled aspects of project complexity from literature

2.3.3 *Megaprojects and project complexity*

Complexity is an embedded issue in megaprojects. A review (Williams 2013) of the work by Williams (2008) stated that this embedded, often high level of, complexity contributes to the unpredictable, poor and often defective delivery of megaprojects. It underlines that the increased socio-political complexity of megaprojects has intensified this faulty delivery. Williams suggests that the concept of, and the issues associated with, complexity are commonly neglected by conventional project management.

Megaprojects intrinsically exhibit characteristics and are often viewed as highly complex (Williams 2013; Remington & Pollack 2007). Megaprojects are usually described by their peculiar attributes, mainly high internal complexity, such as task complexity (Brockmann & Girmscheid 2007), and structural and technical complexity (Remington & Pollack 2007).

Although external complexity is not limited to megaprojects, it often has more significant impact on the outcomes of megaprojects (Hu et al. 2013). Economic instabilities, market fluctuations, and social and cultural transitions can transform megaproject environments into uncertain situations (Shehu & Akintoye 2010). This external uncertainty is categorised with temporal complexity (Remington & Pollack 2007) and social and cultural complexity (Brockmann & Girmscheid 2007). De Camprieu et al. (2007) and Klakegg et al. (2008) argued external complexity merits greater attention in current megaproject research, due to their impacts on several topics, such as stakeholder management, project planning and procurement, project control, and risk management.

2.4 Chapter summary

This chapter has reviewed and discussed the background and literature relating to megaprojects and project complexity. Megaprojects are identified by the size of their capital budget and specific characteristics. At present, they often perform poorly, with significant cost overruns and slips in execution schedules and production shortfalls. A high level of complexity is usually blamed as one of the main causes for failure of megaprojects. This chapter reviewed existing studies on project complexity. The focus was on gaining a better understanding of project complexity by identifying different aspects of this concept. A range of aspects associated with complexity was proposed by different authors, with different levels of generalisation. There is a need to synthesise these further and develope a comprehensive description of project complexity in the context of energy megaprojects.

The next chapter will review existing project complexity assessment methods.

Chapter 3 Project complexity assessment methods

3.1 Introduction

Chapter 3 reviews state of the art in methods and tools for project complexity assessment (PCA). First, it reviews academic studies on complexity assessment methods (Section 3.2); then evaluates several complexity assessment tools used in practice in different contexts (Section 3.3). In order to gain an insight into the current practice in this segment of the energy sector, a preliminary investigation is carried out through interviews with professionals; the results are presented in Section 3.4.

3.2 Complexity assessment methods research

The emergence of large and complex projects has motivated studies on this topic, starting from the early 90's. Conventional tools and methods of project management have not been effective in addressing the issue of project complexity. Remington & Pollack (2007) stated that managing complex projects requires new and effective approaches that are above and beyond those conventional methods used to manage normal projects.

In recent years, there have been a growing number of studies on project complexity (Remington & Pollack, 2007); many of these focus on exploring the concept of project complexity and determining the characteristics of complex projects (Geraldi et al. 2011). Although various researchers have recognised the importance of objective and quantitative measurement of project complexity (Little et al. 1998; Williams 2002), existing studies are mostly devoted to its theoretical and conceptual aspects (Maylor et al. 2008; Kardes et al. 2013), such as developing project complexity frameworks and models. Some of these works were discussed in Chapter 2 (Williams, 2005; Dvir et al., 2006; Geraldi et al., 2011; Bosch-Rekveldt et al., 2011). Others authors, who put forward various methods to obtain an index of complexity, are reviewed in the following three sub-sections.

3.2.1 *Process-based methods*

These methods view project delivery as a process with multiple interrelated activities. They use process analysis techniques to define and evaluate project complexity. Examples include research by Davis (1973), Davies (1975) and Kaimann (1974); they all adopted a coefficient of network complexity (CNC) model to measure the level of complexity of a critical path network. Temperley (1982) applied a measure of complexity based on charts and the relationships of activities in a project. Latva-Koivisto (2001) adopted process charts for measuring complexity of the resource-constrained project scheduling problem. Nassar & Hegab (2006) suggested measuring complexity of project schedules, based on the inter-connectivity of activities. This method defines the degree of interconnectivity among the activities on node (AON) networks of the project's schedule by calculating the number of relationships in a schedule, using the following formulae:

$$C_n = 100 \times \frac{[\log(a/(n-1))]}{[\log((n^2-1)/4(n-1))]} \; if \text{ n } is\ odd$$

$$C_n = 100 \times \frac{[\log(a/(n-1))]}{[\log(n^2/4(n-1))]} \; if \text{ n } is\ even$$

where *n* stands for the number of activities (nodes) in the project and *a* is the number of arcs in the network diagram, *Cn* represents the measure of network complexity in percentage.

The method has the advantage of being fairly intuitive, because minimum and maximum values are presented as a percentage (0 and 100%). However, it is not easy to translate those values to a true understanding of complexity for a project.

In general, the process-based methods have several limitations when used to evaluate project complexity. First, they only focus on a single aspect of complexity, mostly in terms of interdependencies between tasks. Second, these methods concentrate on the structural aspects of a process and mostly ignore organisational and technical aspects. A project can be modelled using different networks, (e.g. PERT networks or Gantt charts) and the resulting model often depends on the perception and skill of the project management team. Thus, these measures are highly dependent on the management team. Finally, these methods rely on a fully developed project schedule as input; they are not suitable for assessment at the early stages of a project. This study adopts a broader view of project complexity, which is different from the rather narrow view of process-based methods.

3.2.2 *Numerical methods*

Methods of this type consider a project as a system and seek to model the dynamics between different system elements, as well as project complexity, using mathematical formulae. An example of this category is the work by Gidado (1996) who identified seven complexity factors that are important for project success. They are *i) lack of complete speciation for the activities, ii) unfamiliarity of the inputs and/or environment, iii) lack of uniformity of work, iv) unpredictability of the environment, v) number of technologies, vi) rigidity of sequence between the various main operations*, and *vii) the overlap of stages or elements of construction*. To measure complexity, a numerical method is developed to measure the impact of project complexity factors on project success, with a particular focus on production time and cost. Two complexity measures are proposed using the following formulae:

$$C_p = \sum C_n T_n / \sum T_n$$

$$C_v = (V_{tot}/V) - 1$$

> where C_p is a measure of complexity for project versus time, C_v is a measure of complexity for project versus cost, C_n is complexity of element *n*, T_n is total time of element *n*, V_{tot} is total cost of the project and V is aggregation of the total direct production cost and the total indirect cost.

A similar method was proposed by Sinha et al., (2006). The method is based on three elements: the number of activities, the number of sub-tasks, and interrelations between sub-tasks. The method employs Shannon's information theory (Shannon, 1948) to calculate a measure of each element in four different levels of information content. These values are aggregated to obtain a complexity index (CI). The CI value is used to categorise projects into simple, medium complex and extremely complex, and enables the project manager to adopt appropriate actions to minimise any impacts caused by complexity.

The main criticism of this type of method is that it adopts a rather mechanical view towards project complexity. They simplify the phenomenon of project uncertainties using a limited number of variables. Consequently, their validity is questionable. It is certainly difficult to achieve the main objective of project complexity assessment: that is to reveal the intricacies between the multi-facets of a project, so that they can be better understood and managed by project management professionals.

3.2.3 *Framework type methods*

Methods of this type intend to propose a structured way of assessing project complexity. They usually define what to measure; how to measure; and how to interpret the results. As an example, Vidal et al. (2011) developed a comparative complexity measurement method, which aims to compare different alternatives; in their case different projects. The authors proposed a framework containing 18 complexity drivers (indicators) grouped in four categories: size, variety, interdependencies and context-dependence. They then proposed a method to calculate weights of drivers using the Analytic Hierarchy Process (AHP). Instead of measuring against objective scales, different alternatives are measured against one another. The aim of such an assessment is to establish a complexity ranking order of several alternatives. The application of the method is demonstrated through a case study within a start-up firm in the entertainment industry. The general approach of this method offers good lessons for this study. However, improvement needs to be made in some key aspects. This method produces ranking of alternatives for a project according to its complexity. However, it does not reveal the true level of complexity for the project. The use of AHP, as a method to rank the alternatives, is not implemented in a robust way; consistency of pair-wise comparisons in the AHP process is not tested, which may lead to unreliable results.

A five-dimensional model has been developed by Owens et al. (2011); context and finance were added to the traditional project dimensions of cost, time and design for measuring the complexity of transportation projects. The method relies on interviews for collecting data during the assessment. The interviewees are asked to simply score each dimension from 10 to 100 in terms of complexity. The results are supposed to highlight sources of complexity. The final complexity scores are presented in a graphical diagram to compare the different complexity levels. This method deals with project complexity from only five project delivery dimensions, which do not provide a comprehensive coverage of sources and elements of project complexity. There is also no distinction for possible differences in relative importance of different dimensions. Its biggest weakness is its exclusive reliance on the subjective judgements of the interviewees, instead of more objective criteria.

Xia & Chan (2012) proposed a relatively simple complexity measurement method to apply to building projects. Their method only contains six indicators: building structure & function; construction method; the urgency of the project schedule; project size/scale; geological condition; and neighbouring environment. Weights of indicators are calculated from the importance index using a five-point Likert scale. The strength of this method lies in its use of three rounds of Delphi-based negotiation involving a panel of experts to establish the importance of indices. To measure the level of consensus, the Kendall's coefficient of concordance (W) is computed to indicate the degree of agreement between experts. Finally a complexity index is calculated by summing up individual weights of criteria. The method showed strengths in measuring project complexity, by extracting opinions from a panel of experts. But its applicability to non-building projects may be hampered by its use of few complexity indicators. Also to use the Delphi method to obtain ranking directly, as is done in this case, together with weights of indicators, is only appropriate when the problem is simple and indicators are limited in number (Linstone & Turoff 1975). For more complex projects, other methods are needed. Finally, scoring criteria for the complexity indicators are not defined.

Very recently, He et al., (2015) proposed a construction project complexity measurement model comprising of 28 complexity factors in the following six categories: technological, organisational, goal, environmental, cultural and information complexities. The authors used fuzzy analytic network process (FANP) and two rounds of Delphi method to obtain individual weights for these factors. The use of the method was illustrated in a construction megaproject case study. The complexity level of each individual factor was evaluated using a questionnaire survey; however, the scale and process of evaluation is unknown. The complexity level of each category was calculated by multiplying weight of category and complexity levels of factors in that category. Finally the overall complexity score was obtained by aggregating the categories' complexity levels. One advantage of this model is adopting actions based on the calculated complexity level to simplify the complexities in the case study megaproject. Also the identification of weights in categories helps to facilitate a higher level analysis of complexity. The model, however, showed some weaknesses. For instance, this model did not define scoring criteria for the factors, which is essential for quantifying the complexity of a new project. The sources used for identifying the complexity factors are not comprehensive. In addition, the application of FANP has not been recognised in practice (Locatelli & Mancini 2012) and the final user may face difficulty in understanding and utilising the method. It is usually mandatory to satisfy consistency of experts' judgments in FANP's pairwise comparison matrices to achieve reliability and validity of results; yet no process is introduced in this study to secure the consistency. Nevertheless, a number of good lessons have been taken on board in this study. Table 3-1 shows a summary of the analysis of the existing project complexity assessment frameworks.

Table 3-1: Comparison of selected complexity assessment methods in research

	Owens et al. (2011)	Vidal et al. (2011)	Xia & Chan (2012)	He et al. (2015)
Focus of the method	To measure complexity of transportation projects	To compare complexity level of different projects	Measuring complexity of building projects	Measuring complexity of construction megaprojects
Assessment procedures and outcomes	Five delivery dimensions of project: context, finance, cost, time and design are considered. Interviews were used to score each dimension from 10-100. Final scores are presented in a graphical diagram.	A four dimensional framework including 18 drivers developed. AHP was applied to obtain the weights and complexity ranks of projects.	Using a five-point scale in three rounds of Delphi to obtain relative importance of complexity indicators, Kendall's coefficient of concordance to calculate levels of agreement between experts	28 complexity factors grouped in six categories. The FANP and two rounds of Delphi method obtained individual weights of factors. Questionnaire surveys evaluated the complexity level of each individual factor.
Strengths	The graphical presentation is intuitive for users	- Effective for comparing projects - Used system thinking to construct the framework - Used case study to test validity	- Applying experts review (Delphi) to establish weights of indicators - Considering consensus among experts	- Adopting actions based on the calculated complexity level - Identification of weights in categories - Relatively complete list of indicators
Limitations	- This method only focuses on delivery dimensions - No weights for dimensions established - The evaluation is subjective	- It is not applicable to measure complexity of one defined project. - Consistency of pair-wise comparisons is not tested	- Very few indicators (6) proposed - No objective criteria to evaluate the indicators - Method is only applicable when the problem is simple	- No scoring criteria for factors defined. - Identification of factors was not comprehensive - FANP is not recognised in practice - No procedure to evaluate the consistency

3.3 Complexity assessment methods in practice

Methods in practice are often termed as methods of project complexity evaluation and assessment. Some of these methods are used for assessing complexity in order to manage it; others aim to assess complexity in order to facilitate selection of project manager/team by matching competencies with levels of project complexity. A desk-based search has identified several practice-oriented methods, including the PMI method, the Project Complexity and Risk Assessment tool (PCRA) from the Treasury Board of the Canadian Government, the Helmsman Institute method, and the Global Alliance for Project Performance Standards method. These methods are discussed below.

3.3.1 *PMI method*

The Project Management Institute (PMI) is a US based independent professional organisation for project management, with over 300,000 members worldwide. Its PMBOK is a widely accepted project management standard guide. In a recent update of the guide, it introduced the concept of complex project management (CPM) (PMI, 2014). The evaluation of complexity in this guide is developed based on the work of Hass (2007), which introduces and evaluates dimensions of complexity that exist on a particular project, so that the project team can take the proper complexity management decisions. The dimensions include project time, team size, team composition and performance, project urgency, schedule, cost flexibility, clarity of the problem and solution, requirements validity, strategic importance, level of organisational change, external constraints, political implications, and level of commercial change. Rather than using a numerical score, each factor is assessed using a three point scale: highly complex, moderately complex and independent. Depending on the complexity profile of all factors, the whole project is also labelled using the same scale from a complexity perspective. Scale thresholds are defined for all factors in a project complexity formula; *Table 3-2* shows an excerpt. Some of the thresholds are defined in explicit quantifiable terms, such as time, cost and team size, which will make the assessment easy for these factors. Others are defined in qualitative terms, such as team composition and performance; assessment of qualitative factors will not be as straightforward. Because the PMI guide can be applied in multiple sectors, the quantitative thresholds may not necessarily be appropriate to specific sectors. They are certainly not suitable for megaprojects in the energy sector. Another criticism of this PMI method, from the perspective of this study, is that the complexity factors are not sufficiently detailed.

Table 3-2. Excerpt of PMI's project complexity formula

Complexity Dimensions	Project Profile		
	Independent	Moderately Complex	Highly Complex
Time / Cost	< 3 months < $250K	3 – 6 months $250K – $750K	> 6 months > $750K
Team Size	3 – 4 team members	5 – 10 team members	> 10 team members
Team Composition and Performance	Strong project leadership Team staffed internally, has worked together in the past, and has a track record of reliable estimates Formal, proven PM, BA, SE methodology with QA and QC processes defined and operational	Competent project leadership Team staffed with internal and external resources; internal staff have worked together in the past, has a track record of reliable estimates Contract for external resources is straightforward; contractor performance known Semi-formal methodology with QA/QC processes defined	Project manager inexperienced in leading complex projects Complex team structure of varying competencies, (*e.g.*, contractor teams, virtual teams, culturally diverse teams, outsourced teams) Complex contracts; contractor performance unknown Diverse methodologies

3.3.2 *Project Complexity and Risk Assessment Tool (PCRA)*

The project complexity and risk assessment tool (PCRA) is developed to support the Treasury Board of the Canadian Government on the management of projects (Treasury Board of Canada Secretariat, 2009). The tool provided a list of 64 complexity indicators to evaluate the level of complexity of prospective or ongoing projects of government. The indicators are categorised in six groups: project characteristics, strategic risk management, procurement risk, human resource, project management integration, and project requirement. Each indicator is phrased in a form of a question. Depending on the answer to the question, the indicator is scored a value of 1 to 5. Table 3-3 shows example indicators and their scoring criteria. All indicators, as questions, are equally weighted; the total score for a project is a simple tally of scores for all indicators.

Table 3-3: Example indicators related to "costs"

Question	Clarification	Rating
1. What is the total project cost estimate?	• The inherent complexity and risk of the project may increase with the size of the project. • Complexity normally increases when more money is being managed and the impact of realised risks increases. • The total project cost estimate is to be either an indicative cost estimate or a substantive cost estimate.	1 = $1-5 million 2 = $5-10 million 3 = $10-25 million 4 = $25-100 million 5 = over $100 million
2. What percentage of the total project cost estimate is for procurement?	• The inherent complexity and risk of the project may increase with more procurement. • When more of the project is being procured, rather than supplied internally, the initiative is considered more complex.	1 = No procurement is required—answer "1" to all questions in the "Procurement risks" section (3.3). 2 = under 25 per cent 3 = 26-50 per cent 4 = 51-75 per cent 5 = over 75 per cent

The final score of a project is rated at four levels: 'sustaining' (with a score less than 45), 'tactical' (a score of 45-63), 'evolutionary' (a score of 64-82), and 'transformational' (a score of 83 and over). This indicates a sliding scale of complexity and risk: 'sustaining' representing the least complex and lowest risk. At the other end of the spectrum, 'transformational' represents projects of the highest complexity, that require extensive capabilities for their successful delivery. The strengths of this method lie in the comprehensive list of complexity indicators and objective scoring criteria. However, the theoretical basis of the definitions of indicators and the scoring criteria are unclear. Also the identification of factors and categories is not consistent. Indicators with similar meaning appeared in different groups, leading to potential distortion of the final assessment result. Another clear weakness of this method is the lack of appropriate weighting for different indicators. In reality, some indicators matter more than others to project complexity.

3.3.3 *Helmsman Institute method*

Helmsman Institute is an Australia based international consultancy company. It developed a framework to measure and compare project complexity within and across organisations and industries (Helmsman Institute, 2009). The framework identified five main areas of complexity in projects: context, sociological factors, ambiguity, technical, and management. Each of these areas is further divided into more specific complexity indicators; resulting in a total of 47 complexity factors. The factors are scored in a 1-10 scale and their evaluation is subjective, as it is based on an assessor's opinion. To obtain a project's overall complexity score, all factors' scores are aggregated and normalised in a 1-10 range. Helmsman institute introduced a "Helmsman complexity scale" measure which ranks and categorises projects based on their overall complexity. The scale (Table 3-4) ranges from 1 to 10, and is intended to mimic the Richter earthquake scale in terms of significance. The ranking of projects, based on the scale, enables the comparison of complexity levels among projects, as well as facilitating the adoption of suitable complexity management strategies. This framework is applied by the Australian Ministry of Defence in assessment of the complexity of the Defence Materiel Organisation (DMO) procurement project portfolio, which is compared with other industries. The APM group (APMG), a well-known global accreditation body, also implemented the Helmsman institute project complexity framework in their APMG maturity index (APMG, 2013). The project complexity score is used in a maturity index as one of the main identifying criteria to define the project management maturity levels. The strengths of the Helmsman istitute framework are its fairly comprehensive list of complexity indicators, its relatively simple method of assessment, and its suitability for different sectors. However, one of its main weaknesses is that its scoring is very subjective and no specific rating criteria are proposed. Another significant weakness is that all indicators are considered to have the same importance; no weight or ranking is suggested.

Table 3-4: Helmsman complexity scale (Helmsman Institute, 2011)

Scale	Level	Project Characteristics	Examples
< 4	Minor/ Micro	One person may be full time, designated team	Build new custom home
4 - 5	Organisationally Simple	Often performed by professional project teams on a regular basis	Product maintenance and competitive enhancements to ongoing business operations
5 - 6	Organisationally Normal	Standard core projects in the top 50-100 organisations	Regulatory, environmental, business upgrades. GST, Y2K, clean fuels
6 - 7	Organisationally Complex	Most complex projects commonly undertaken across the top 50-100 organisations	Merger integration, core system replacement. A380 introduction
7 - 8	Nationally Complex	Most complex projects commonly undertaken in the nation	BHP Olympic dam, Broadband rollout. Some defence projects
8 - 9	Nationally significant	Creates significant impact on national economy	Snowy river scheme, Olympics, Collins
9 - 10	International	Significant multi-national project	Hadron collider, Apollo, joint strike fighter, BASEL II
10.0 +	Global	No truly global project has yet been executed	Joint global warming project

3.3.4 *Global Alliance for Project Performance Standards (GAPPS)*

The Global Alliance for Project Performance Standards (GAPPS) is a non-profit organisation that provides independent reference benchmarks for project management standards and assessments. It provided a framework (GAPPS 2007) to classify projects based on their management complexity, by using a tool known as CIFTER developed by Aitken & Crawford (2007). The tool analyses complexity through seven project management complexity factors: stability, number of distinct disciplines, magnitude of implication, expected financial impact, strategic importance, stakeholder cohesion, and number of interfaces for complexity of project. A four-point scale is used to score each factor: very high (1), high (2), moderate (3), and low or very low (4). The total score for a project is a simple sum of scores for all factors. The strength of this method is its simplicity; project managers can use it and gain a quick overview of complexity for their project. However, simplicity also contributes to its weakness. Complexity indicators are too generalised. The scoring criteria are very subjective. Any result it produces is more of a perceived complexity from the perspective of the person who carries out the assessment. It is not suitable for complexity assessment in a descriptive approach, which is the approach adopted by this study.

Table 3-5 shows the comparison of complexity assessment methods in practice. Each of these methods has strengths and weaknesses. None of them is suitable for complexity assessment for megaprojects in the energy sector for the following reasons. First, the indicators of these methods do not accurately reflect the multiple facets of energy megaprojects. There is a need for more comprehensive and more relevant complexity indicators to apply within the domain of this study. Second, none of these methods adopts weights to distinguish the relative importance of different indicators. Objective scoring criteria are only used in some of these methods, and they are not appropriate for megaprojects. Once new complexity indicators are identified, corresponding objective scoring criteria will also need to be defined.

Table 3-5: Comparison of complexity assessment methods in practice

	PMI (2014); Hass (2007)	Treasury Board of Canada Secretariat (2009)	Helmsman Institute (2009)	GAPPS (2007); Aitken & Crawford (2007)
Measurement criteria	13 complexity factors are identified. For each factor three descriptive criteria categorise a project's profile.	64 indicators are identified and categorised into six groups. For each indicator numerical rating is a 1-5 scale.	47 factors are suggested and categorised in five areas. A 1-10 scale evaluates the complexity level of each factor.	7 complexity factors suggested and a 1-4 scale of low, moderate, high & very high measures them.
Scoring method	Rather than calculating a single complexity score, method obtains complexity level of each factor in three levels: highly complex, moderately complex and independent	The aggregation of indicators scores to produce a project complexity score. It then ranks the project in one of four levels, sustaining, tactical, evolutionary and transformational.	Aggregation of factors' scores obtains project complexity score.	The aggregation of factors' scores linearly calculates the final complexity level.
Strengths	- The method is widely accepted and used in practice - Proposing rating criteria for factors	- List of indicators, categorisation and numerical rating is provided - For each score a management level is suggested	- Method is accepted and used by both public and private sector - Simple assessment method	- Simple to apply
Limitations	- The definition of rating criteria is simplistic and arbitrary - Very few factors suggested - No weight is established	- No theoretical background for each element of method - Identification of indicators is not consistent - - No weight or rank for factors	- - Scoring is very subjective without any rating criteria assigned to scaled - No weight or rank for factors	- Only few factors are identified - Subjective scoring due to lack of ratings - No weights for factors -

3.4 Preliminary empirical investigation

This study sought to evaluate the current project complexity assessment practice in large energy companies. Unfortunately, no company was willing to provide access to such information due to its commercial sensitivity and confidentiality. It was, therefore, decided to gain some insight of the views of industry insiders through interviews with professionals who are working in this sector. The interviews explored professionals' perceptions of project complexity; their views on complexity management and requirement for effective complexity assessment methods. Semi-structured interviews were performed with six professional experts from the energy sector (oil & gas, as well as renewables), who have extensive experience of the management of complex projects. Table 3-6 shows a summary of the experts' profiles.

Table 3-6: Summary of the background information of the experts

Interviewee	Experience in Energy	Sector	Experience with Megaprojects
Expert1	18	Renewable/Offshore/Oil & Gas/Infrastructure	Advanced
Expert2	16	Renewable/Onshore/Offshore	Knowledgeable
Expert3	20	Renewable/Onshore/Offshore	Knowledgeable
Expert4	30	Subsidiaries/Oil & Gas	Expert
Expert5	23	Energy/Oil & Gas/Upstream & Downstream	Expert
Expert6	14	Oil & Gas/Subsea/ Renewables	Advanced

As it can be seen from Table 3-6, the experience of the interviewees ranges from 14 to 30 years. All experts have a high level of knowledge of megaprojects in various energy sub-sectors.

An interview guide was designed to ensure alignment of questions with the research objectives (Table 3-7). The interview guide consists of two sections. The first section obtains background information of the interviewee. It includes questions about their experience in the energy sector and familiarity with the management of megaprojects. The second section explores the perception of experts about project complexity, current complexity evaluation/management methods and its differences with conventional project management methods e.g. risk management. Then it asks for the experts' opinions about the use of complexity evaluation/management in the energy sector, with a focus on two key elements (who? when?). Finally, it asks for the experts' opinions about the need for a PCA method in practice, and its requirements.

Interviews were carried out in the location of the interviewees' office for their convenience and time efficiency. The sequence of questions did not have to follow the outline of the interview guide, but depended on the flow of the conversation. Also sometimes extra questions were asked, when the interviewees discussed topics which were considered to be important and relevant to the subject of the interview. All interviews were fully audio-recorded with the permission from the interviewees.

Table 3-7: Interview guides

Project Complexity Assessment in Energy Megaprojects **Interviews with Experts**
Introduction This interview will investigate project complexity assessment in the field of energy megaprojects. The interview will be based on a semi-structured and face-to-face model. The following questions are organised in 4 sections and provide the main body of the interview. However during the interview, some discussions may be further explored and points elaborated. The total time of interview is aimed to be maximum 60 minutes. The interview will be audio-recorded with the consent of the interviewee. The identity of interviewees will be kept confidential, as required by Heriot-Watt University.
Respondent's background 1.1 How many years of experience do you have? 1.2 What is your professional sector? ☐Oil & Gas ☐Renewable ☐Utility

☐Consultancy

☐Construction

☐Contractors

☐Other (Please specify): ………………………………………………….

1.3 Rank your knowledge and experience level in general megaprojects, and in the energy sector in particular, using the following guidelines:
(Please tick inside the cell below your desired answer)

	Familiar	**Knowledgeable**	**Advanced**	**Expert**
Megaprojects	☐	☐	☐	☐
Energy	☐	☐	☐	☐

Familiar	You have general knowledge about the topic, but have not practically applied it.
Knowledgeable	You feel you have a proficient level of knowledge about the topic. You have read about the topic and formed some opinions about it.
Advanced	You were once an expert, but feel somewhat rusty now, or are in the process of becoming an expert but still have some way to go to achieve mastery of the topic; or you work in a neighbouring field and occasionally draw upon or contribute to the development of the topic.
Expert	You consider yourself to belong to the community of people who currently dedicate themselves to the topic matter, and are recognised outside of your organisation as having a strong grasp of trends or other aspects of the topic.

Guidance questions for interview

1. How would you define a complex project? Or what does the term "project complexity" mean to you?
2. What is the current trend for complexity evaluation? How does a project complexity assessment (PCA) differ from other project evaluation

methods e.g. risk management?

3. In terms of undertaking PCA, what is your view on:
   a. Who should be responsible for the PCA process?
   b. When should PCA be applied? (drafting, initiation, or operation)
4. What is the real need for a PCA method? What characteristics should a PCA method have?

The analysis of the interviews was carried out after all the interviews had been transcribed. At this stage, this study employs the qualitative and inductive approach, hence, it is based on less structured procedures and relies more on the researcher's interpretation for analysing the data. The analysis is divided into four sections each focusing on one question of the interview.

Question 1

The question mainly explores beyond the linguistic definition to understand and demonstrate the underlying features of complex projects based on the experts' perceptions.

The question is somehow difficult to answer, because there is a lack of an industry-wide standard definition about "complex project" and "project complexity". As a result, some experts struggled to come up with precise answers; for example:

"That is precisely what I am trying to understand, I don't think any word can explain it, if it is not complex, so it is simple, more unclear now, what is simple?......... project complexity does not help, complexity in terms of what?........."

Other experts expressed their opinion about project complexity by referring to different project features e.g. technology, people,

"I prefer using the term technology difficulties rather than the complexity… it is the mix of known and unknown and varieties. People in projects; some are experienced some are not, so the complexity is more relative."

"Complex projects are projects which contain many people with different experiences, possibly projects are in different locations, countries or even continents… they are some causes of complexity."

It appears that professionals do not worry much about a neat definition of “complex project” or “project complexity”. Instead, they are more concerned with the relevant aspects that characterise this type of project, such as technology difficulties, uncertainty, people, multi-stakeholders, multi-locations and project management methods.

The relevance of perceived complexity is also found in the following quote:

“I think that really varies, depends on from whose view it is looked ... perspectives of a project manager or operation manager to distinguish a complex situation like technology issues are different from those of a technical manager”.

Question 2

This question explores the existing methods that specifically evaluate the complexity of projects. It also investigates if these methods exist, how they are distinguished from other project management methods, e.g. risk management. The most significant result is that none of the experts can point to any specific method or tools for assessing project complexity. It also appeared that complexity assessment is neither performed as a formal process nor is it clearly given status at an organisational level, compared to the other well-established project management methods. Although a few aspects of project complexity are evaluated and measured using other tools, such as technical tools to evaluate the complexity and risk of an exploration process, this does not cover the comprehensive nature of the overall complexity of a project.

Experts highlighted risk management as the most used tool, which may address some complex aspects of a specific project:

“In most of the projects I have dealt with, a risk assessment procedure at the front end is done; however I reckon it is more business driven than technological.”

The emphasis of experts is mostly put on the importance of technical issues and associated uncertainties that cause risks. The experts also highlighted the weaknesses of conventional risk management approaches and the fact that many failures have not been avoided in practice. In addition, a number of other tools are currently used for evaluating projects in the early stages, such as cost-benefit analysis (CBA), or specific-business-oriented (SBO) tools, which only partially address complexity matters.

Question 3

This question asks experts' opinions about key elements in implementing a PCA method:

> *Who:* the main person or team responsible for performing the process in the organisation. Experts gave a variety of answers to this, including project teams, operation managers, contractors and consultants. In addition, all experts agreed that project managers or executive are the owners of the PCA process and should drive it.
>
> *When:* is the stage of project that the PCA should be implemented? The experts favour complexity assessment at the early project stages, such as a feasibility study, project initiation and briefing.
>
> *'In my opinion, at the launch of the project it is very important to understand the complexity, and it is very valuable if you have some way of measuring it, and classifying based on different factors."*

Early implementation of PCA methods benefits subsequent decision-making tasks, such as project selection, resource allocation, project tendering and sanctioning. Two experts also pointed out the PCA process should not only be carried out at the beginning, but should be carried out throughout the project, at different points, such as when major decisions are made.

Question 4

This question attempts to disclose opinions of the experts about the need for a practical and effective PCA method. Although the experts had not experienced any effective complexity assessment tool, all of them strongly supported the need for developing such an idea. They also identified several aspects of complexity that any new complexity assessment method should address:

- External complexity: environmental, political
- People complexity
- Technical complexity

They also outlined some characteristics that the new method should have:

- Quantitative and adequate

- Highlighting the sources and causes of complexity
- Clearly distinguished from other methods, e.g. risk management

The interviews found that project complexity is not addressed as an identifiable subject of analysis and management, even for very complex projects. However, professionals do recognise the relevance and impact of key aspect of complexity, such as technical difficulties, problems caused by multi-stakeholders, and high degrees of uncertainty. At present, some of these factors are considered as part of risk management, but not in any systematic way. The interviewees felt strongly that a dedicated project complexity assessment method would help to analyse the numerous facets of complex projects, so that they could be better understood and better managed. The professionals also provided some suggestions about the characteristics of such a method. These will be taken into account in the subsequent work of this study.

3.5 Chapter summary

This chapter reviewed existing methods of complexity assessment in academia and practice. The main features of these methods are discussed, together with an analysis of their strengths and weaknesses from the perspective of complexity assessment of megaprojects. The preliminary empirical investigation revealed the current lack of dedicated complexity assessment methods in practice in the energy sector. The need for such a method, or methods, is evident in that many megaprojects fail, due to high levels of complexity, coupled with a lack of effective management of that very complexity. The review in this chapter has revealed some of the essential requirements for a new project complexity assessment method; it should cover the assessment of a comprehensive list of aspects that are relevant to project complexity. Any such method should be able to assess these aspects in a quantitative manner. These key conclusions will guide the research approach of this study. The next chapter contains a detailed description of this matter.

Chapter 4 Research Methodology

4.1 Introduction

The aim of this chapter is to explain and justify the research methodology adopted for this study. It begins with a discussion of the research philosophy that underlines all scientific research (Section 4.2); then explores different research approaches that are available to choose from (Section 4.3). Section 4.4 offers a detailed description of the research methods selected for this study, as well as justification for their selection.

4.2 Research philosophy

Positivism and phenomenology are the two main research paradigms employed by researchers to investigate the truth and facts about the real world. Realism is sometimes considered as another paradigm (Saunders et al. 2012), close to positivism, but Bryman & Bell (2011) did not recognise it as a separate paradigm, only as a component of positivism. Different terms are used for these two main terminologies, as listed below (Mangan et al. 2013):

- Positivist paradigm: quantitative, objectivist, scientific, experimentalist, traditionalist, hypothetico- deductive, social, constructivism

- Phenomenological paradigm: qualitative, subjectivist, humanistic, interpretive / hermeneutic, inductive.

Positivism is defined by Bryman & Bell (2011) as "an epistemological position that advocates the application of the methods of the natural sciences to the study of social reality and beyond". The positivist approach is based on organised research methodologies that use experimental and quantitative methods to evaluate hypothetico-deductive generalisations. The phenomenological approach mainly regards realisation of behaviours from the researchers' own subjective settings of reference. In this approach, research methods are to test and define, translate and describe, and to interpret situations from the perspectives of the people who undertake the research. The positivist approach is often supported by deductive research and the phenomenological approach tends towards inductive research.

Given the aim and objectives of this research, the positivist philosophy seems to broadly fit this study, as the research focuses on the understanding and objective quantifying of project complexity for energy megaprojects. However, the lack of any subjectivity associated with positivism is sometimes criticised as it only sees human behaviour as passive and controlled by the external environment. (Saunders et al. 2012). People and social organisation are an integral part of the focus of this present study. The research can only be carried out on a selected project as a case study, and with the involvement of a limited number of experts. Therefore, a pure positivist approach would not be appropriate. The best fit for the research is to utilise both positivism and phenomenological philosophies. It will involve values and methods that should be quantified and developed using deductive methods, and also thought and work to be explored and synthesised using an inductive approach. These principles are further expanded when the justification for the research approaches is discussed and explained in the following sections.

4.3 Research approaches

Authors have used different terms to define research approaches, and regardless of the notion used, these research paradigms imply a variety of research techniques for data collection (Thomas 2004). The main dimensions are:

- qualitative / quantitative
- deductive / inductive

The next sections discuss each of the above dimensions.

4.3.1 *Qualitative / Quantitative Approach*

Qualitative research is more subjective than the quantitative paradigm and includes investigating and reflecting on the less measurable aspects of a research subject, e.g. values, attitudes, perceptions. Hussey & Hussey (1997) defined qualitative research as "a subjective approach which includes examining and reflecting on perceptions in order to gain understanding of social and human activities". A qualitative approach is often used when it is needed to reveal a person's experience or behaviour, to create an in-depth analysis of a specific process of a single case study or limited number of cases, and to understand a phenomenon, about which there is very little information (Ghauri &

Gronhaug 2001). The data collection methods for qualitative research include interviews, documents and texts, observations (field work), focus groups, and the researcher's perception about a social phenomenon (Saunders et al. 2012).

Quantitative research, as opposite to qualitative research, is as objective as possible. It supports collecting and analysing numerical data; it emphasises measuring the scale, range and frequency of a phenomenon or matter. Quantitative research, although initially more challenging to design, is usually greatly detailed and structured, and results can be effectively collated and analysed statistically. The data collection methods for quantitative research may include questionnaires and surveys.

Both qualitative and quantitative approaches can be used in either positivism or phenomenological philosophies and/or used in various research strategies (Oates 2006). Researchers may employ either quantitative or qualitative methods in one study, resulting in a multi-method or mixed-method approach. Mixed-method also refers to 'triangulation' which is the use of different data collection or analysis techniques within one study, in order to improve confidence in the results.

On the basis of points raised in the above discussions, a mixed-method approach is believed appropriate for this research. The study will use a qualitative approach to explore and synthesise the literature of project complexity and megaprojects, and a quantitative approach to investigate different alternatives from the viewpoints of experts, using the Delphi group decision making paradigm.

4.3.2 *Deductive / Inductive*

Another two main concepts of reasoning are the deductive and inductive approaches. Easterby-Smith et al. (1991) and Saunders et al. (2012) stated research always encompasses the use of theory, while Bryman & Bell (2011) argue that the main concern in the relationship between research and theory is whether research is done to test the existing theory or to develop a new one.

In the deductive approach a theory and/or hypotheses are developed and then a strategy is planned to test the hypotheses; while in the inductive approach data is collected and a theory is developed based upon the results of the data analysis (Saunders et al. 2012). The deductive approach orients from the more general to the more specific level, known as the "top-down" approach, initiating with a theory, narrowing down into specific hypotheses and finally testing them. The inductive approach applies in the opposite way, moving from particular observations or experiments to larger generalisations and theories, known as the "bottom-up" approach. This model involves initiating specific measures, identifying patterns, formulating some empirical hypotheses or assumptions to be investigated, and finally concluding with developing some general suggestions or a theory.

This research will adopt both inductive and deductive approaches. During the early stages, interviews (inductive) will be used to gather opinions of experts regarding practical needs for, and current trends of, assessing the matter of project complexity. Literature review and synthesis (inductive) are used to establish a taxonomy of project complexity indicators early in this study; as well as to define the scoring criteria for these indicators. Later, the research moves on to use a questionnaire survey (deductive) and integrated Delphi-AHP techniques to obtain the rankings and weights of the complexity indicators. Finally, a case study (deductive) is used to get an in-depth understanding about the application in practice of the developed project complexity assessment method.

4.4 Research methods for this study

There are numerous alternative research methods to choose from. The essential consideration is applicability and suitability of the selected method to the research problem and objectives (Thomas 2004). A number of research methods are employed in this research including (1) literature review and synthesis, (2) semi-structured interviews, (3) integrated Delphi-AHP process, (4) expert review and (5) case study.

4.4.1 *Literature review and synthesis*

A literature review is a key initial stage of a research project, used to identify and justify research questions and the research design (Creswell 2009; Bryman & Bell 2011). The goal of the literature review is not simply to present the findings from the sources, but to critically evaluate the relevant concepts, theories and opinions of existing studies. This study conducts literature review in three stages:

(1) The initial review helps to identify the gaps in knowledge in the fields of project complexity assessment and energy megaprojects; as well as shortcoming of

existing complexity assessment methods and tools. The findings were presented in Chapters 2 and 3 respectively.

(2) A review and qualitative synthesis of the literature is also the principal method used to develop a taxonomy of project complexity indicators. This is achieved through two steps: first a systematic review is carried out to identify the sources for extracting indicators; then a qualitative synthesis is conducted to establish a meaningful structure of the taxonomy of PCIs. Details are presented in Chapter 5.

(3) At a later stage of this study, a further literature review is undertaken to establish numerical scoring criteria for project complexity indicators. For this, an interpretive synthesis of the literature is carried out to extract information, based on which objective scoring criteria are defined. This is presented in Chapter 7.

4.4.2 *Interviews*

Saunders et al. (2012) stated that structured interviews are based on pre-determined and standardised questions, while semi-structured interviews rely on themes and questions to be addressed. The list of themes and questions may differ in each semi-structured interview and the data yield from the interview will depend on how the conversation progresses.

Semi-structured interviews are conducted in this study to assess the credibility of the research questions and objectives. The interviews aim to complement the literature review's findings and provide a pragmatic perspective of the needs and problems relative to the assessment of megaproject complexity in the energy sector. Interviews are performed with six experts from the energy sector (oil & gas, as well as renewables), who have extensive experience in the field of complex project management. The input from these experts enhances the research justification and help to ensure the relevance of the research in practice. The results of the interviews were presented in Chapter 3.

4.4.3 *Delphi and AHP methods*

The Delphi technique has been developed to obtain the most reliable consensus of a group of experts (Okoli & Pawlowski 2004). This method has been used in a wide variety of situations, as a method for expert problem solving. The Delphi approach has also been proved efficient to build group consensus about the relative importance of issues (Schmidt 1997). Two or more rounds of questionnaires are usually used to gather inputs independently from a panel of experts. After each round, the respondents are encouraged to revise their earlier answers in light of the replies of other members of their panel. This process is repeated until group consensus is reached.

The analytical hierarchy process (AHP) was developed to improve decision making and results, when one is faced with a mix of qualitative, quantitative, and sometimes conflicting factors that need to be considered (Saaty 2003). The AHP has been demonstrated as effective in making complicated and complex decisions (Al-Harbi 2001). It uses the judgments of decision makers to establish a breakdown of problems into a hierarchy. Decision makers present their judgements about different factors and alternatives in the form of pair-wise comparisons. The results show ranking among factors.

This research uses both AHP and Delphi in an integrated process, to obtain the relative ranking and weight of project complexity indicators, while a degree of consensus among experts is reached. Twenty experts with high levels of knowledge about energy megaprojects participated in this process and are equally grouped into two panels of academics and professionals. More detailed discussion is provided in Section 4.5.

4.4.4 *Expert review*

Once all research data acquisition and analysis stages have been performed, the credibility of the research findings should be evaluated. The researcher's responsibility is to reduce the possibility of wrong or erroneous results through the research design process. Reducing the likelihood of obtaining wrong outputs requires the researcher to assess both *validity* and *reliability* (Saunders et al. 2012). Validity relates to the accuracy of the findings: "does the research measure what it intends to measure?" (Collis & Hussey 2013; Bryman & Bell 2011; Quinlan 2011). Validity of research may be evaluated based on qualitative or quantitative approaches and in different ways. Reliability is usually regarded as a measure of the repeatability of the research results. Repeatability refers to the capacity of other researchers to achieve the same results by repeating the same experiment (Collis & Hussey 2013; Bryman & Bell 2011; Quinlan 2011).

In order to establish the reliability and validity of this research, expert review and case study paradigms are adopted. Since the inclusion of the PCI indicators in the taxonomy and their weights are produced based on experts input, there is no need for additional evaluation of their validity. Therefore, the expert review approach is focused on validating the numerical scoring criteria for all the PCI indicators.

For evaluation, experts are selected, who are not involved in the Delphi-AHP process. This ensures a higher level of independence of the evaluation. A questionnaire is used for collecting feedback from experts. The questionnaire contains closed-ended, yes/no questions to capture agreement or disagreement, and open-ended questions to enable the user to state underlying reasons (particularly in the case of disagreement). Nine experts participated in this review and provided valuable feedback which was used to evaluate and refine the numerical scoring criteria of PCIs. This review is presented in Chapter 7.

4.4.5 *Case study*

The stability and consistency of a solution and transferability of research denote the need for a case study strategy. Conducting a case study also demonstrates the practical application of research findings. Yin (2009) explained the case study as a means to explore many situations, many fields and at all levels. This method provides an opportunity for researchers to explore and gain detailed understanding of phenomena from real life situations.

For this research, an energy megaproject is chosen as the case study to demonstrate the practical implementation of the developed PCA method. A project team, including project managers, collaborated in the process and provided useful feedback from the project setting. They were able to evaluate the level of complexity of energy megaprojects using a developed (spreadsheet) tool that implements the PCA method for energy megaprojects which had been developed in this research. The details of this work are presented in Chapter 8.

4.5 Integrated Delphi-AHP method

The application of an integrated Delphi-AHP method is at the centre of this study. All problem-solving requires the application of knowledge to the problem (De Bruijn & Leijten 2007). It is even more sensitive in the case of large complex projects (Priemus, Flyvbjerg & van Wee 2008). For complicated problems, such as the evaluation of project complexity of megaprojects, the process requires knowledge and information from many disciplines, and requires the consideration and input of multiple opinions (Krishnaswamy & Sivakumar 2009). It means that this study involves making decisions based on the feedback from a group of experts. In recent years, some studies have proposed group decision making (GDM) techniques to provide consistent results obtained from the analysis of knowledge and opinions of groups of experts, instead of single persons (Hwang & Lin 1987; Saaty 1989; Herrera-Viedma et al. 2007; Moreno-Jiménez et al. 2007). The GDM method is defined as a process to find a plural answer to a decision problem, where a group of experts offer their judgments about multiple alternatives (Zhang et al. 2014).

In this study, the development of a taxonomy identifies a list of project complexity indicators. The next step is to determine how much each indicator should count when assessing the overall complexity of a project. The opinions of 20 international experts are sought in order to establish the relative importance of the indicators. For tackling similar problems, Herrera-Viedma et al. (2002) proposed a method involving two processes: a *prioritising process* and *consensus process*.

1) *The prioritising process* is used to gather the view from each expert about the ranking of indicators in order of relative importance.

2) *The consensus process* is designed to achieve the optimal degree of consensus or agreement among a group of experts regarding the solution with a set of alternatives.

There are a number of methods for each of these two processes, which are discussed in the following sections with the aim of selecting the most appropriate methods for this research.

4.5.1 *Prioritising process*

The prioritising process includes all tasks to determine and rank the candidate alternatives of the solution. A number of tools and methods have been proposed for the process of prioritising (Ribeiro 1996), including the *Analytical Hierarchy Process* (AHP), *elimination* and *choice translating reality* (ELECTRE), *preference ranking organisation* for *enrichment evaluation* (PROMETHEE), and *technique* for *order* of *preference* by *similarity* to *ideal solution* (TOPSIS). Table 4-1 shows a comparison of these methods.

ELECTRE

The ELECTRE method was first introduced by Roy & Vanderpooten (1997) as a comprehensive evaluation approach, in which alternatives are ranked based on pair-wise comparisons. It measures rank difference for each pair of alternatives and outlines two strong and weak relationships using graphs (Vahdani et al. 2010). An exploitation procedure is used to gain recommendations from the results obtained from the pair-wise comparisons. The type of recommendation is related to the tasks in the procedure (choosing, ranking or sorting). The ELECTRE is applicable when at least three alternatives are included in a decision making process. However, a combination procedure should be adopted in situations when decision problems include more than five criteria (up to twelve or thirteen).

TOPSIS

TOPSIS (Hwang & Yoon 1981) is built upon a theory that the selected alternative should have the shortest geometric distance from the *positive ideal solution* (PIS) and the furthest geometric distance from the *negative ideal solution* (NIS). In the process of TOPSIS, the performance scores and the weights of the criteria are considered as crisp values. A crisp value indicates whether an element is a member of the set or not. For instance, car A belongs to the class of vehicles known as sedans and car B does not. TOPSIS is a method of compensatory accumulation that compares a set of alternatives by determining weights for each criterion and normalising the scores. An assumption of TOPSIS is that the criteria are uniformly growing or reducing. Normalisation is usually necessary in the process because the criteria are often in incompatible dimensions in the decision making problems (Yoon & Hwang 1995).

PROMETHEE

The PROMETHEE method was developed by Brans (1982) and further expanded by Vincke & Brans (1985). PROMETHEE is an outranking method for a limited number of alternatives, often conflicting. It is based on the pair-wise comparison of alternatives in each criterion. Alternatives are assessed according to different criteria, which have to be maximised or minimised. The application of the method entails two additional types of information: I) the weight which is defined by the decision-maker when the number of criteria is not too large; II) the preference function for each criterion which interprets the variance between the evaluations obtained by two alternatives into a preference degree ranging from zero to one. The application of PROMETHEE in practice is difficult, due to the need for extra functions during the process.

AHP

The AHP (Saaty 1980) is used to define priorities and make the optimal decision between sets of alternatives. It is a multiple criteria decision-making method based on the Eigen value approach and the pair-wise comparisons. It builds a problem in a hierarchy of different levels: goal, criteria, sub-criteria and alternatives. It offers a methodology to regulate the numerical scale for measuring both quantitative and qualitative performances. The maximum Eigen value, consistency index (CI), and normalised values for each criteria/alternative are calculated from the pair-wise comparison judgments. If the maximum Eigen value and CI are satisfactory, then a decision will be made based on the calculated normalised values; otherwise the process should be repeated till these values fit in a desired range. AHP does not directly help to reach a group consensus process, as it basically considers one set of judgments in each round of calculations; instead AHP helps reaching *individual consistency*. Therefore, other methods, which complement AHP, must be used to ensure consensus.

Table 4-1: Comparison of prioritising methods modified from (Locatelli & Mancini 2012)

Prioritising Method	Advantage	Disadvantage	Reference
ELECTRE	• It is developed upon specific outranking relations, less limiting than dominance relations. • The results are ranked, so they are easily understood. • Each decision matrix can be normalised, and then every attribute can be explained in its particular unit of assessment. • Well-constructed method.	• It determines a limited set of preferable options, instead of the best solution. • Subjective values could greatly impact final results. User should maintain two thresholds for adjusting the performance of criteria. • It regards only a number of criteria for each alternative. • It does not include the real present gaps in criteria.	(Zanakis et al. 1998; Pohekar & Ramachandran 2004; Figueira et al. 2005; Kiker et al. 2005; Yoon & Hwang 1995; Georgopoulou et al. 1997; Beccali et al. 1998)
TOPSIS	• It includes comparisons for both a positive ideal solution and a negative ideal solution. • Each decision matrix can be normalised, and then every attribute can be explained in its particular unit of assessment. • It includes the real gap between scores of different alternatives rather than simply	• The method is not applicable in some problems, as positive and negative ideal measures may be meaningless in those situations. • It is more effective with engaging many alternatives and fewer criteria.	(Figueira et al. 2005; Opricovic & Tzeng 2004; Zanakis et al. 1998; Yoon & Hwang 1995; Hwang & Lin 1987)

	counting the number of outranked attributes for a cut-off. • The process is intuitive.		
PROMETHEE	• Different measures of preference can be defined between two alternatives by determining the thresholds. • Non-linear preferences can be obtained by providing the thresholds and similar indices.	• The thresholds may be inaccurate because they are very subjective. • It is more effective with engaging many alternatives and fewer criteria. • The method is complex and less consistent with the higher number of criteria.	(Nowak 2005; Kiker et al. 2005; Figueira et al. 2005; Pohekar & Ramachandran 2004; Haralambopoulos & Polatidis 2003)

AHP	• It can be efficiently used in combination of qualitative and quantitative assessments of alternatives. • A flexible method which can be applied in many problems. • Complex problem can be broken down to a simpler hierarchical form, easing its analysis. • Using pairwise comparisons provides productive and simple way to elicit weights of alternatives. • It requires the consistency of expert judgments. • The relative rank of alternatives can be directly elicited from expert judgments and does not need a detailed value for each character of alternatives. • It is a well-constructed method.	• It involves many judgments from experts if there are many alternatives. • The process of breaking down a complex problem to a hierarchical structure is very subjective.	(Saaty 1989; Saaty 1990; Vaidya & Kumar 2006; Kiker et al. 2005; Figueira et al. 2005; Hämäläinen 1990; Yoon & Hwang 1995; Jain & Nag 1996; Korpela & Tuominen 1996; Salo & Hämäläinen 1997; Zanakis et al. 1998; Adler & Ziglio 1996; Al-Harbi 2001; Cheng et al. 2002)

In this research, AHP is preferred over the other methods. It seems more effective and reliable than the alternatives. In fact, AHP has already been effectively adopted in similar studies by others. Nguyen et al. (2015) developed an AHP-based approach to measure the overall complexity of transportation projects and applied it in three case studies. The results showed that the method enabled the project teams to better manage complex transportation projects. Vidal et al. (2011) defined a measure of project complexity for analysing projects in a portfolio. They conducted a critical review in order to identify the most appropriate tool. Then, they identified the AHP method as the most appropriate method for assessing project complexity.

The AHP process has three stages (Ishizaka & Labib 2011): problem modelling, weights valuation and weights aggregation which are discussed here.

1) Problem modelling

AHP uses a hierarchical structure to analyse the problem, which brings a clearer insight onto the specific criteria and sub-criteria when determining the weights. This structuring stage is essential, because a different structure may result in different final weights (Pöyhönen et al. 1997). It has also been shown by Stillwell et al. (1987) and Weber et al. (1988) that criteria with a large number of sub-criteria seem to receive a larger overall weight than when they are less detailed. Thus, it is suggested that each large criterion be classified into some clusters to avoid bias rankings (Ishizaka & Lusti 2004; Saaty 1991).

2) Weights valuation

This stage comprises identifying judgement scales and conducting pair-wise comparisons.

Judgment scales: one of AHP's advantages is its ability to evaluate quantitative as well as qualitative criteria and alternatives on the same preference scale. The final ranking of alternatives is presented by numerical values (e.g. here weight of PCIs), so the preference scale to calculate the ranking must be numerical. However it can be verbally or graphically presented in the pair-wise comparisons, as this is easier to comprehend. Verbal responses are commonly used because of such an approach is more user-friendly (Table 4-2).

Table 4-2: Scale of verbal measurement

Intensity of relative importance	Definition
1	Equally important or preferred
3	Slightly more important or preferred
5	Strongly more important or preferred
7	Very strongly more important or preferred
9	Extremely more important or preferred
2, 4, 6, 8	Intermediate values

The linear scale, with the integers one to nine and their reciprocals, has been used most commonly in research and practice and was highlighted by Saaty (1990) as the best scale to signify weight ratios.

Pair-wise comparisons: Psychologists stated that it is simpler and more precise to express one's opinion on only two alternatives than simultaneously on all the alternatives (Ishizaka & Lusti 2006). It also permits consistency cross-checking between all pair-wise judgments. All pair-wise judgments of all alternatives are logged in a positive reciprocal matrix (Figure 4-1) called the pair-wise comparison matrix (PCM); where a_{ij} stands for the par-wise judgment value between alternative *i* and *j* and *n* is the number of alternatives.

$$\begin{bmatrix} 1 & a_{12} & \cdots & a_{1i} & \cdots & a_{1j} & \cdots & a_{1n} \\ 1/a_{12} & 1 & \cdots & a_{2i} & \cdots & a_{2j} & \cdots & a_{2n} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1/a_{1i} & 1/a_{2i} & \cdots & 1 & \cdots & a_{ij} & \cdots & a_{in} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1/a_{1j} & 1/a_{2j} & \cdots & 1/a_{ij} & \cdots & 1 & \cdots & a_{jn} \\ \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots & \cdots \\ 1/a_{1n} & 1/a_{2n} & \cdots & 1/a_{in} & \cdots & 1/a_{jn} & \cdots & 1 \end{bmatrix}$$

Figure 4-1: AHP pairwise comparison matrix

3) Weights aggregation

This stage includes priorities derivation, consistency checking and final aggregation.

Priorities derivation: The aim is to obtain a set of priorities $p_1 \ldots p_n$ such that p_i/p_j match the comparisons a_{ij} in a consistent matrix. Several methods have been proposed to obtain those priorities. Saaty proposed using the mean of the row as in the formula below:

$$\text{Mean of row } i\text{:}\ p_i = \frac{\sum_{i=1}^{n} \left(\frac{a_{ij}}{\sum_{i=1}^{n} a_{ij}} \right)}{n} \qquad (4$$

In the case of the existence of small inconsistencies, this may produce only a small distortion. Based on this idea, (Saaty 1977) proposed to use the principal Eigen vector ***P*** as the desired priorities vector based on perturbation theory. He stated that minor variations in a consistent matrix infer unimportant variations of the Eigen vector and the Eigen value:

$$A \times P = \lambda \times P \qquad (5$$

Where **A** is the comparison matrix; **P** is the priorities vector; **λ** is the maximal eigenvalue.

However, Johnson et al. (1979) demonstrated a rank reversal problem for scale inversion with the eigenvalue method. A rank reversal problem involves a change in the rank ordering of the alternative and occurs when ranking of elements depends on the formulation of the problem. It also may be caused by the addition or deletion of an alternative. To address this problem, the geometric mean (also sometimes known as logarithmic least squares method) has been proposed and adopted by a large number of researchers (Aguarón et al. 2003).

Consistency checking: As priorities are valid only if resulting from consistent or near consistent judgments, a consistency check must be conducted. Inconsistency can be due to psychological reasons (e.g. imperfect information, uncertainty and lack of attention during the judgment process), clerical errors, and an insufficient model structure (Sugden 1985). There is another issue which motivated contemporary researchers and provided them a new insight into this problem, which emerged as in GDM problems: consensus of judgments of multiple experts is usually reached on the basis of rationality principles that each expert exhibits (Herrera-Viedma et al. 2005). The requirement of rationality demands consistency of judgement from each individual expert. Therefore, consistency checking and consensus reaching processes should be both considered.

Many integrated methods and techniques for this aim have been developed based on both cardinal and ordinal consistency, which are reviewed and discussed in depth in this section.

Consistency is generally divided into two types:

- ***Cardinal consistency (CC):*** The judgments of decision makers are cardinally consistent, if the following conditions are met (Saaty 1980):

  - $a_{ij} = \frac{1}{a_{ji}}$ for all *i and j;*

  - $a_{ij} = a_{ik} a_{kj}$ for all *i, j* and *k*

  In such a case, the decision maker *A* is said to be (completely) consistent.

  Saaty (1977) suggested a consistency measure based on the largest Eigen value for a specific PCM. Given that for a consistent positive reciprocal matrix, the largest Eigen value λ_{max} is equal to n, the following consistency index (CI) can be calculated:

$$CI = \frac{\lambda_{\max} - n}{n-1} \qquad (6$$

  where n is the dimension of the matrix; $\lambda_{\max}$ is maximal Eigen value. The consistency ratio (CR) is then given by:

$$CR = CI / RI \qquad (7$$

  Where *RI* is the random index (the average *CI* of 500 randomly filled matrices). The PCM is recognised as an acceptable judgment when the threshold of $CR \leq 0.1$ is met. Nonetheless, if $CR > 0.1$, the assessed priorities could be inaccurate, and decision makers must be requested to improve the consistency by revising their judgments (Vaidya & Kumar 2006).

Chu et al. (1979) chose the mean square error (residual) as a measure of inconsistency. Likewise, Crawford & Williams (1985a) suggested the logarithmic residual mean square (LRMS) as an ordinary measure of consistency, for the geometric mean (GM) method. Aguarón & Moreno-Jiménez (2003) established LRMS and termed it the *geometric consistency index* (GCI), calculated as:

$$GCI = \tfrac{2}{n(n-1)} \sum_{i=1}^{n-1} \sum_{j>i}^{n} (\log(a_{ij}) - \log(\tfrac{w_i}{wj})) \qquad (8$$

where w is a priority vector, estimated by using the geometric mean method. The relation between GCI and CR is considered nearly linear for $CR \leq 0.1$.

While CR is widely applied, it has been much challenged for its two major downsides i.e. sensitivity to scale (Kuenz Murphy 1993; Stein & Mizzi 2007) and the threshold value of $CR \leq 0.1$. GCI exhibits the same limitation, having a linear relationship with CR. CR also is criticised rigorously because it permits contradictory judgements in matrices (Bana e Costa & Vansnick 2008) or rejects reasonable matrices (Karapetrovic & Rosenbloom 1999). Normally, if the PCMs are ordinally consistent, most prioritisation methods obtain priorities with the same weights, or with only slight differences. If, however, the matrices are ordinally inconsistent (intransitive), different prioritisation methods provide different ordinal rankings that are moderately related to the ordinal comparison judgments (Siraj 2011).

- ***Ordinal consistency (transitivity)****:* ordinal consistency (OC), which is also identified as the transitivity condition between three criteria, indicates that if E_i is preferred to E_j and E_j is preferred to E_k, then E_i should be preferred to E_k. Using the preference symbol →, OC is identified as:

  If $E_i \rightarrow E_j \rightarrow E_k$ then $E_i \rightarrow E_k$

  a. The preference judgments indicate ordinal inconsistency (or intransitive) if $E_k \rightarrow E_i$ when $E_i \rightarrow E_j \rightarrow E_k$. Therefore, ordinal inconsistency can be distinguished as $E_i \rightarrow E_j \rightarrow E_k \rightarrow E_i$, which represents a "*circular triad of preferences"* (Kendall & Smith 1940).

Ordinal inconsistency always entails cardinal inconsistency; however, the reverse is not true. CR or GCI measure the cardinal inconsistency of the judgments, but do not evaluate ordinal inconsistency. Mostly, if a PCM is ordinally inconsistent, the value of its CR stays higher than 0.1; therefore assuring the CR threshold may reduce the ordinal inconsistency. Several methods have been developed to measure ordinal consistency (or transitivity), i.e. Kendall's (Kendall 1955) coefficient of consistence, ζ.

Final aggregation

This step synthesises the local priorities across all criteria to obtain the global priorities. The conventional AHP approach (also called distributive mode) uses an additive aggregation with normalisation of the sum of the local priorities:

$$p_i = \sum_j w_j \times l_{ij} \qquad (9$$

where p_i is the global priority of the alternative *i*; l_{ij} is local priority; w_j is weight of the criterion *j*.

The distributive mode depends on rank reversal, a phenomenon that has been extensively discussed and challenged in the literature (Belton & Gear 1983; Wang & Elhag 2006). The subject of priorities derivation (here weights of indicators) in AHP has been discussed by Ishizaka and Lusti (2006) in order to establish the best method in this subject A review of their study and other literature leads to the classification of weight calculation methods in two categories: the Eigen value vector (EV) and geometric mean (GM) vector methods (Saaty 1977; Johnson et al. 1979). The EV method obtains a scale of the importance of each element of a collection, relative to the others, while GM yields priority of elements using the geometric mean distance metric. Crawford & Williams (1985) conducted an extensive comparison of these two categories of methods, using statistical and simulation analysis, and demonstrated a better performance of the geometric mean method over the Eigen value methods. Vargas (1997) also argued that the GM is the only confident method to regain exact weights of known objects. Thus, this method has been applied in this research. Given p_{ij} a preference relation between indicator i and j in a $n \times n$ judgment matrix, $i \neq j$, the consolidated weight of indicator i ,w_i, is obtained with the GM formula as follows:

$$w_i = \prod_{j=1}^{n} p_{ij}^{1/n} \quad (10$$

The GM has non-linearity features yielding a superior compromise to be chosen, which is not the case with the additive aggregation (Stam & Duarte Silva 2003).

A note about weights of experts

Another consideration when establishing criteria ranking and weights is to give different weights to the judgements of different experts (Yue 2012). Experts may vary according to their level of knowledge, social environment and personal experience. The process of GDM should reflect such variations. One of the critical factors of correctness and rationality of the decision-making solution is reasonableness of the experts' weights (Liu et al. 2015). Several methods of expert weight determination have been developed for GDM, and can be divided into subjective and objective methods. Subjective expert weighting methods have been applied in some AHP applications and require each participating expert to intuitively rank other panel experts (Ramanathan & Ganesh 1995; Linstone & Turoff 1975). However, the drawbacks of these methods are that the subjectivity of experts is too strong; in addition informing experts about each other breaches the anonymity requirement of the Delphi method. On the other hand, objective methods define experts' weighting based on the judgment and information they provide, but the procedure dealing with the weights of experts is very complex (Yue 2012). Instead of choosing one explicit expert weighting, this research devised a new strategy based on defining three different scenarios which adopt different weighting methods. The details of the application of this strategy are explained in Chapter 7. The process of AHP is shown in Figure 4-2.

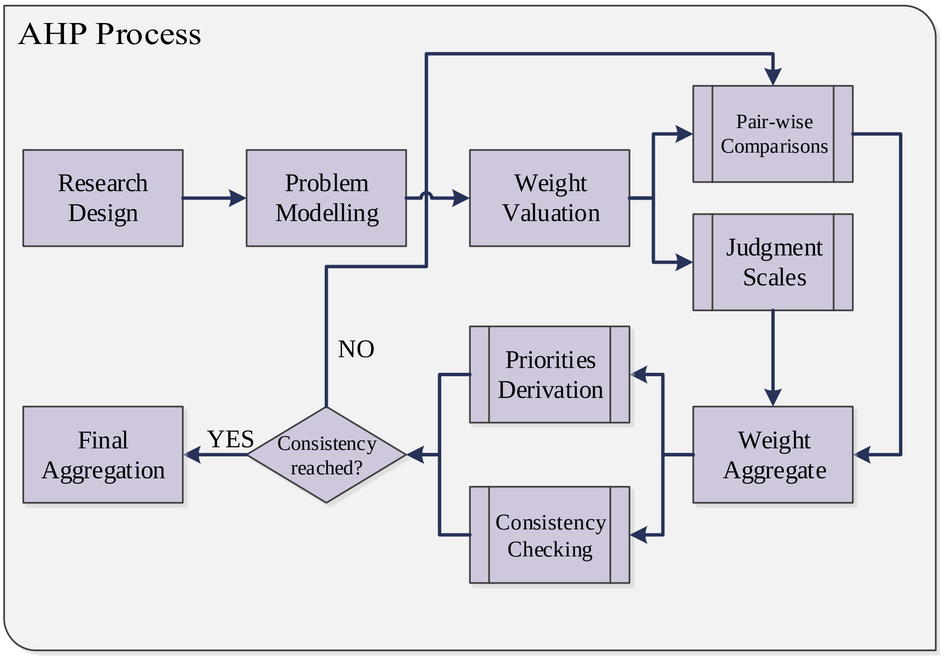


Figure 4-2: Summarised AHP process

4.5.2 *Consensus Process*

Consensus in GDM is a process used to produce common levels of agreement. Herrera-Viedma et al. (2005) mentioned five attributes that are important for obtaining consensus during a group decision making process, as set out below:

- Inclusive: as many qualified experts as possible participate in the group.
- Participatory: all participating experts have an equal chance to contribute to the discussion.
- Collaborative: the group produces proposals with input from all participating experts. Group decisions should consider the opinions of all experts.
- Agreement seeking: the aim is to produce as much agreement as feasible. The group is committed to making decisions through consensus.
- Cooperative: each individual opinion should be considered so that the group can integrate all opinions into an emerging proposal. However, individual opinions should not obstruct the progress of the group.

A number of methods have been developed and used to achieve consensus in decision making such as brainstorming, nominal group technique (NGT) and Delphi. However among these methods, the Delphi method is widely recognised as the most efficient and reliable method for obtaining informed consensus (He et al. 2015).

The Delphi method

The Delphi method is an iterative process to collect and elicit the anonymous judgments of experts, using sets of data collection and analysis techniques, together with feedback. The Delphi method is well suited as a research tool when there is partial knowledge about a problem or phenomenon (Skulmoski et al. 2007). The Delphi method has been widely applied in research in the area of strategic studies and project management (Schmidt et al. 2001). The anonymity of the participants is an important benefit of Delphi, because it avoids self-censorship (error of spiral of silence), and provides experts with the flexibility to amend their judgments as they learn from the results of iterative rounds (error of group-think). The isolated process also removes negative group impacts such as dominating participants (error of leadership) and political lobbying. Delphi has proven productive when integrated with other methods when the process of problem solving entails using of number of different methods either qualitative and quantitative (Mousavi et al. 2012; Tavana et al. 1993; Azadeh et al. 2009). Delphi has also recently been implemented in the PCA methods for prioritising the PCIs (Xia & Chan 2012; He et al. 2015).

Another advantage of the Delphi method for this research is its ability to be conducted remotely. Indeed, in the proposed research, which investigates PCA for energy megaprojects, the pool of experts that could participate is truly international, and it would be an extremely challenging task to co-locate them for interviews, brainstorming or other face-to-face options.

Several features of the Delphi procedure include anonymity, iterative structure, asynchronicity, and controlled feedback are worthy of note:

- Anonymity: participants are anonymous and cannot contact each other in person; thus, the opinions of each person in a panel are hidden from the others. Anonymity also permits the participants to freely express their ideas without pressure to adapt to other’s opinion in the group (Keeney et al. 2001).
- Iterative structure: because the collection of judgments takes place in several iterations, the participants can peacefully review and refine their assessments based on the provided feedback. (Landeta 2006).

- Asynchronicity: the participants interact through a facilitator at a distance and at different times without any of the anxiety created by classic synchronous meetings.
- Controlled feedback: the feedback informs the participants' perspectives and collective judgments of other members and provides the opportunity for experts to clarify or modify their views (Linstone & Turoff 1975).

Delphi studies can be classified into different types. *Classical Delphi* is the basic type (Dalkey & Helmer 1963) which focuses on extracting opinion and reaching consensus amongst participants in a particular research area through a series of rounds, normally three or more. Postal communication is typically used in this type. *Policy Delphi* is another type which is similar to classical Delphi, but the aims is to produce opposing opinions on a particular issue such as policy making (Hasson & Keeney 2011). *Decision Delphi* tries to establish a decision making structure, and selects the participants from their actual positions in the decision-making hierarchy of their organisations (Rauch 1979).

Conventional Delphi is the most common Delphi model found in current research. It aims at generating consensus through sequential rounds. At each round, questionnaires are submitted to the participants, the results are analysed. If the consensus level is not sufficient, another round is conducted, and the iterations continue until consensus is achieved (van Zolingen & Klaassen 2003). *Real-time Delphi* also called "the expert workshop" or "the one-day group Delphi" (van Zolingen & Klaassen 2003) follows a similar process as conventional Delphi but with a different communication type. It aims at reducing the time and number of rounds by arranging a meeting where all invited experts meet together to solve a particular problem. Note that, in this case, the feature of anonymity cannot be kept. Furthermore, the workshop needs to be facilitated by a computer system to provide summaries of results in real-time.

Regarding anonymity, different locations, and convenience of communication tools, *real-time* and *classical* Delphi are not appropriate to apply in this current research project. Also the study aims to reach agreement among experts which is not the feature of *policy* Delphi. Therefore the *conventional Delphi* option has been chosen for this study. Skulmoski et al. (2007) outlined some considerations that should be taken into account in order to avoid yielding invalid results in the process of employing the Delphi approach:

- Choice of methodology: while the Delphi method can be implemented in either qualitative, quantitative or mixed methods research design, the characteristics of the given context can dictate the most appropriate methodology (Adler & Ziglio 1996).

- Level of experience of participants: the Delphi experts must satisfy four competency requirements: i) experience and familiarity with the subject of research; ii) capability and will to participate; iii) enough time for participation; and, iv) effective communication abilities (Holsapple & Joshi 2002).

- Number of experts: a practical consideration should be the participant sample size, or panel size. The panel size usually varies from 10 to 18 members, which guarantees a high level of knowledge overall (Okoli & Pawlowski 2004).

- Number of rounds: the number of rounds depends on the objectives of the research and required level of consensus. Usually two or three iterations are needed for most research subjects, informed by the availability and interest of participants (Skulmoski et al. 2007).

- Expert selection: the selection of the most suitable experts has a critical impact on the success of Delphi. This study adopted a multi-stage process based on the guidelines of Okoli & Pawlowski (2004) to identify the experts. In the first stage, a knowledge resource nomination worksheet (KRNW) has been developed to help classify the experts before selecting them, in order to avoid neglecting any important category of experts. In the second stage, actual expert candidates are identified to populate the KRNW categories. The third and fourth stages involve contacting the nominated experts to invite them to participate in the study and ranking those who accept. The results of this process are presented in Chapter 6.

The main steps of Delphi (Adler & Ziglio 1996; Delbecq et al. 1975; Linstone & Turoff 1975; Skulmoski et al. 2006) are summarised as follows for a two round study (Figure 4-3):

(1) The design of the research in the Delphi process: selecting the most appropriate method(s) to help answering the research question; can be qualitative, quantitative or mixed; the Delphi method may be only one element of the research, the results of Delphi may be verified and generalised with other techniques.

(2) The formation of the panel of experts, based on the four competency requirements.

(3) The development of the Delphi round one questionnaire and its distribution to all experts.

(4) The analysis of results of round one using selected analysis techniques (e.g. qualitative coding or statistical summarising).

(5) The development of the Delphi round two questionnaire and its distribution to individual experts: depending on the research objectives, the researcher may guide the focus of the participants toward a consensus solution.

(6) The analysis of results of round two, similar to analysis of round 1. Even though further rounds are possible, many studies can achieve the required level of consensus after two rounds, as in the case of this study.

(7) The documentation of Delphi results: usually carried out continuously through the Delphi process and includes recording and documenting the results.

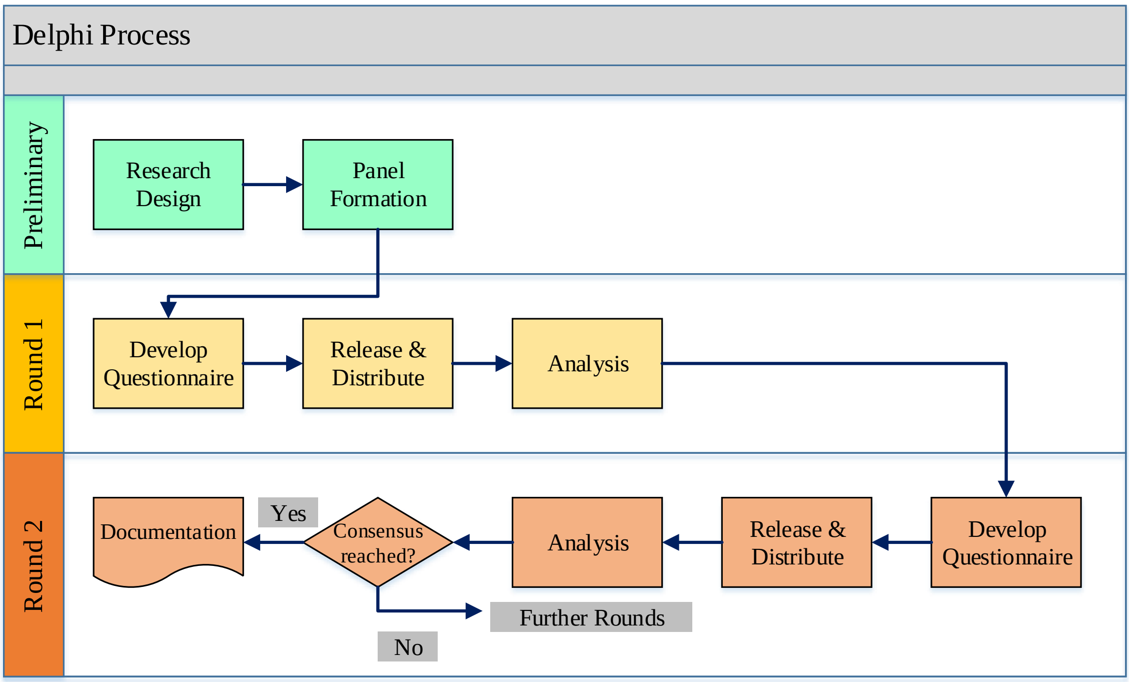


Figure 4-3: Summarised process of Delphi

4.5.3 *Integration of AHP and Delphi*

Delphi and AHP, as an integrated method, has been used in several studies. For instance, Tavana et al. (1993) developed a AHP-Delphi group decision support system for the problem of conflicts in personnel hiring decisions. Huang et al. (2009) firstly used the Delphi method to determine the risk factors of projects, and then AHP to obtain the ranks of factors. Al-Hajri (2006) integrated the Delphi method and AHP to develop a model of information system development methodologies by applying the Delphi for verifying variables and the AHP for evaluating the alternatives. In project complexity measurement, Vidal et al. (2011) developed a framework of project complexity factors and used the Delphi to refine the framework. They establish the AHP as the most appropriate technique for PCA amongst existing multi-criteria decision making methods and used AHP to obtain relative project complexity measures of six projects.

An integrated method of Delphi and the AHP can be applied in two different ways (Ishizaka & Labib 2011):

- In sequence: a Delphi process is used only in the first stage of the AHP, when structuring the hierarchy, and then the rest of the AHP method is carried out as usual.

- In parallel: during the AHP process, the experts express their judgments conforming to the Delphi logic in multiple iterations. In this case, Delphi can be used to both establish the hierarchy and to compile the pair-wise comparison matrices.

The sequential approach, which follows a simple process, is adopted in all the above mentioned instances of Delphi-AHP use. The parallel approach is more effective because it can benefit from the full potential of both methods. Delphi is used to reach a consensus in the pair-wise comparison judgements; at the same time the AHP process grasps the final criteria weights.

This study uses an integrated Delphi-AHP method, which applies the two methods in parallel. It is adapted from a method suggested by Chiclana et al. (2008) but with some additions to it. Figure 4-4 summarises the steps of the integrated Delphi-AHP method, including the process for consistency checking and consensus building. The four main steps are:

(1) Selecting experts: identify, nominate and select the most appropriate experts for the panel.

(2) Delphi-AHP round 1: to elicit the weights of PCIs, the selected experts are asked to express their judgments through a series of pairwise judgements matrices. Responses from each expert are checked for consistency and corrections are applied automatically when required, following the method suggested by Chiclana et al. (2008).

(3) Delphi-AHP round 2 (consensus building): this round builds the required level of consensus through sets of feedback matrices.

(4) Calculating weights for PCIs: the weights of all PCIs are calculated using the geometric mean method. Since one may also attach different weights to different experts, three different scenarios are defined and compared.

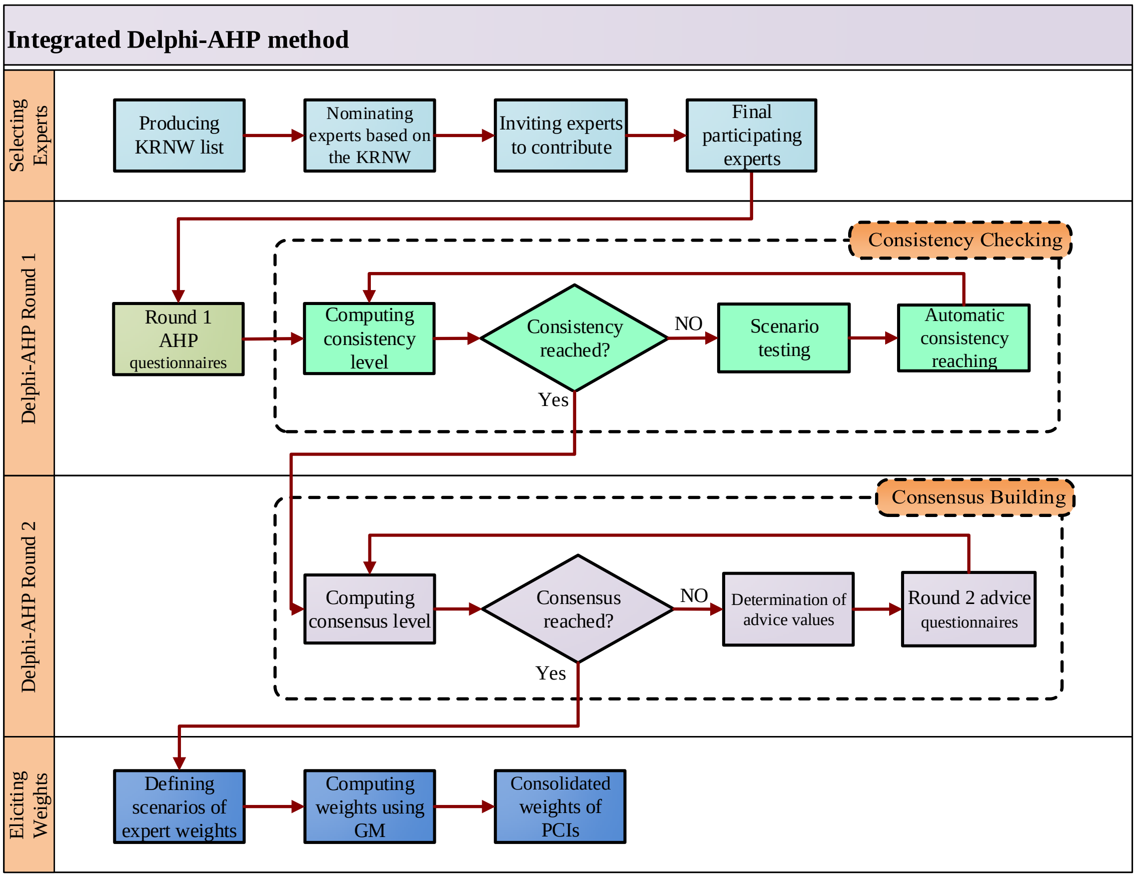


Figure 4-4: Proposed integrated Delphi-AHP process

4.6 Chapter Summary

This chapter described the five research methods used in this study:

(1) literature review to identify research gaps, question and objectives; qualitative/interpretive synthesis to identify the comprehensive list of PCIs and structure them within a taxonomy; and to determine numerical scoring criteria of PCIs;

(2) semi-structured interviews to establish a practice perspective toward project complexity assessment in energy sector;

(3) integrated Delphi-AHP process to compute the weights of indicators,

(4) expert review to confirm validity of numerical scoring criteria, and

(5) case study to test the applicability of developed method in practice.

The integrated Delphi-AHP is at the centre of this study and accounts for the lion's share of the research work. It has been described in detail here. The outcomes of the application of this method are presented in subsequent chapters.

Chapter 5 Development of the Taxonomy of Project Complexity Indicators

5.1 Introduction

This chapter describes the development of a taxonomy for characterising project complexity. It is divided into two main sections. First, in Section 5.2, a list of 110 PCIs is compiled, based on a systematic review of literature; then a qualitative synthesis is conducted to consolidate the list down to 51 indicators. Second, Section 5.3 describes how the 51 indicators are categorised into semantic groups, and how a logical hierarchical structure is developed based on the principles of the PRINCE2 project management standard.

5.2 Selecting project complexity indicators from literature

5.2.1 *Identifying the sources*

In order to identify relevant publications, a systematic literature search was adopted, based on the approach suggested by Geraldi et al. (2011). The Web of Science (WoS) and Scopus databases have been chosen as the sources of an exploratory desktop search. These search engines are the world's largest web sources of peer-reviewed scientific literature and include publications from over 10,000 journals. Web of Science and Scopus are more complementary in scope than overlapping. Based on the scope and objectives of the research, the search used the keywords "complexity" OR "complex" AND "project" in the title/abstract/keyword field under the energy, environment, engineering, management, and business (EEEMB) sub-areas of the search engines; only including publications in the English language. The time period for the publications was set from 1996 to January 2015, because the first journal paper initially found on the topic was the work of Baccarini published in 1996. In order to reduce the likelihood of mising important studies, especially books, which do not appear in the results of search engines, the references of the papers were reviewed in a further search. This considered books, academic conference proceedings and book chapters, but working papers, and notes were discarded; a total of 44 publications was identified.

This study aimed to develop a comprehensive list of project complexity indicators for energy megaprojects. Beside academic publications, there are extensive works on the contexts of megaprojects which are produced by megaprojects' research centres.

However, some of the works appeared in publications, in the form of reports and policies. Therefore, to regard the completeness of source information, a desktop search has been carried out, which identified 5 reports and 1 policy.

In total, 50 information sources were obtained. An analysis of the typology of these resources is presented in Table 5-1.

Table 5-1: Overview of typology of sample in resources

Sector								
Generic	Process	Construction	Defence	Product develop.	IS	Infra-structure	Transport	Energy
16	2	10	1	7	3	2	5	4
Methods								
Theoretical	Qualitative	Quantitative	Qual. & Quan.					
15	10	18	7					
Source								
Journal article	Book	Book Section	Conference Proceeding	Policy	Report			
31	7	1	5	1	5			
Focus								
Megaproject	General							
20	30							

The number of resources in each year (*Figure 5-1*) shows a much higher interest in the topic in terms of publications during the second period of 2006-2015 (65%), than in the first segment of 1996-2005 (35%). One reason for this difference may be because project complexity, as a distinct subject was less known to researchers in the first period of 1996-2006. It is also interesting to note that most of the works on ‘megaprojects’ (or ‘large projects’) have appeared in the literature after 2007. Emergence of large complex projects and the need to study their relevant issues in the early years of 21st century can be counted as an essential reason for the increasing numbers of publications in 2006-2015.

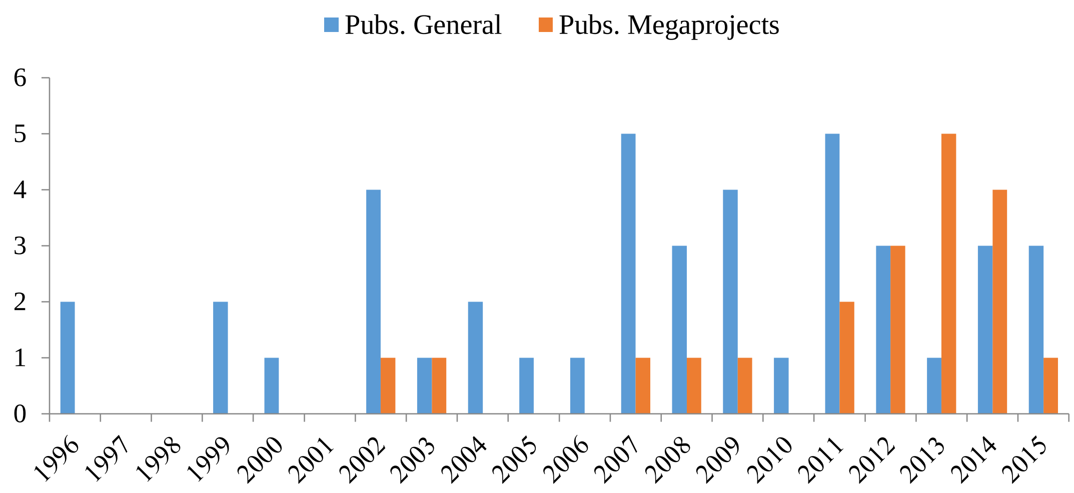


Figure 5-1: Distribution of source publications in year

Regarding the sector on which the sources focus, although sixteen studies were generic, without any particular focus, the construction industry attracted the most attention of all the sectors. The sector-oriented studies were conducted in two ways: some studies investigated the issues of the sector and developed specific models and frameworks for that, such as the works by Tatikonda & Rosenthal (2000) in product development or (Jiang et al. 2008) for construction. Other studies followed a literature analysis to establish a generic basis and then focused the study on a particular field by various means e.g. survey, interview or case study. Examples of this approach are (Remington et al. 2009) in defence and (Giezen 2012a) in transport.

From the analysis of typology in *Table 5-1*, the main types of research methods are identified.

- *Quantitative methods* are the most used method in the sample. Different methods are applied such as a survey, which was used in 8 publications. One of the most common uses of survey is to elicit the ranking for elements of project complexity; for instance Qureshi & Kang (2015) and Nguyen et al. (2015). The case study is another method which is adopted. This method normally targets a small number of projects because of difficulties in the process of data collection; however, it can obtain valuable data for further detailed analysis. This method is used by researchers such as Lu et al. (2014), Lessard et al. (2014) and Merrow (2011).

- *Theoretical studies* proved to be the most popular research model after quantitative methods. Two publications are fully dedicated to literature reviews (Benbya & McKelvey 2006; Geraldi et al. 2011). Subject centred literature reviews are often used as the starting point of research, either for identifying aspects or indicators of project complexity, such as Clift & Vandenbosch (1999), Tatikonda & Rosenthal (2000) and Bosch-Rekveldt et al. (2011), or to establish the theoretical basis, for instance Gransberg et al. (2013), Vidal et al. (2011) and Jiang et al. (2009). Some papers only discussed theoretical concepts of complexity, for example the works of Austin et al. (2002), Jaafari (2003) and Baccarini (1996).

- Ten works including (Maylor et al. 2008; Wood & Ashton 2010) employ *qualitative methods* with interviews being the main method for gathering data. Interviews, in the complexity context, are recognised as a helpful method for gaining collaborative and in-depth information about the sources and contributing elements.

- Seven studies use *mixed qualitative and quantitative methods* including Shenhar (Shenhar & Dvir 1996; Xia & Lee 2004; He et al. 2015).

Table 5-2 presents an overview of the 50 identified sources and information about their focus, sector, applied methods and main complexity aspects in the research.

Table 5-2: Overview of sources identified from literature

	Authors	M / G [1]	Type	Aim	Sector	Methods	Complexity aspects
1	(Baccarini 1996)	G	JA	To explore complexity	Construction	Theoretical	Organisational Technological
2	(Austin et al. 2002)	G	JA	To identify factors for modelling complexity	Construction	Theoretical	Structural
3	(Clift & Vandenbosch 1999)	G	JA	To investigate methods of reducing time in projects	Product development	Case study	Size Technological
4	(Jaafari 2003)	G	JA	To study the relationship of complexity and competency	Generic	Theoretical	Project Environmental
5	(Shenhar & Dvir 1996)	G	JA	To construct a classification of projects	Product development	Qualitative (interviews) and quantitative (survey)	Technological
6	(Williams 1999)	G	JA	To explore complexity and unveil limitations of traditional project management	Generic	Theoretical	Structural Uncertainty
7	(Little 2005)	G	JA	To explore complexity	Information systems	Case study	Structural Uncertainty
8	(Tatikonda & Rosenthal 2000)	G	JA	To study the relationship between product features and outcomes	Product development	Quantitative (survey)	Organisational Technological
9	(Ribbers & Schoo 2002)	G	JA	To study managerial concepts for ERP applications	Product development	Case study	Variety Interdependence

10	(Xia & Lee 2005;2004)	G	JA	To explore complexity	Information systems	Qualitative (interviews) and quantitative (survey)	Structural
11	(Benbya & McKelvey 2006)	G	JA	To investigate sources of complexity	Information systems	Literature review	Organisational Structural Dynamic
12	(Maylor et al. 2008)	G	JA	To explore complexity	Generic	Qualitative (interviews)	Structural Dynamic
13	(Shenhar & Dvir 2007)	G	B	To investigate effects of complexity on project success	Generic	Theoretical	Assembly System Array
14	(Geraldi & Adlbrecht 2007)	G	JA	To explore complexity	Process	Qualitative (interviews)	Fact Faith Interaction
15	(Remington & Pollack 2007)	G	B	To explore complexity and its management tools	Generic	Theoretical	Structural Temporal Technical Directional
16	(Hass 2009)	G	B	To explore complexity and project management	Generic	Theoretical	Number of indicators
17	(Brockmann & Girmscheid 2007)	M	CP	To explore complexity of megaprojects	Construction	Theoretical	Task Social Cultural
18	(Sommer & Loch 2004)	G	JA	To investigate relations of uncertainty and complexity	Product development	Quantitative (Simulation)	Uncertainty Ambiguity
19	(Lane et al. 2002)	M	BS	To solve the dynamic complexity of project development	Construction	Qualitative (Interview)	Technical Uncertainty

20	(Gransberg et al. 2013)	M	JA	To explore the complexity theory for successful delivery of projects	Transport	Qualitative (Interview)	Technical Cost Context Financing Schedule
21	(Cooke-Davies et al. 2007)	G	JA	To investigate contribution of complexity theory in modern project management	Generic	Theoretical	Social Uncertainty
22	(Shafiei-Monfared & Jenab 2012a)	G	JA	To measure the relative complexity	Product development	Theoretical	Technical Managerial
23	(Whitty & Maylor 2009)	M	JA	To explore the project complexity for competency standards	Generic	Theoretical	Political Social Technological Environmental Financial
24	(Jiang et al. 2008)	M	CP	To explore sources of complexity in large projects	Construction	Case study	Technical Environmental Structural
25	(Williams 2002)	G	B	To explore issues of modelling complex projects	Generic	Theoretical	Structural Uncertainty
26	(Wood & Ashton 2010)	G	CP	To identify factors of project complexity	Construction	Qualitative (Interview)	Organisation Technical Uncertainty

27	(Remington et al. 2009)	G	CP	To identify factors of project complexity and their severity	Defence	Qualitative (Interview)	Goals Stakeholders Interfaces Technology Management Work practices Time
28	(Bosch-Rekveldt & Mooi 2008)	G	CP	To review of classification methods of project complexity	Generic	Theoretical	Technical Organisational Environmental
29	(Bosch-Rekveldt et al. 2011)	M	JA	To characterise project complexity of large projects	Process	Case study	Technical Organisational Environmental
30	(Geraldi et al. 2011)	G	JA	To explore the project complexity	Product development	Literature review	Structural Uncertainty Dynamic Pace Socio-political
31	(Lu et al. 2014)	M	JA	To explore a measurement of complexity from perspective of hidden workload	Construction	Case study	Task Organisational
32	(Xia & Chan 2012)	G	JA	To define a measure of project complexity	Construction	Quantitative (survey)	Only indicators identified
33	(Vidal et al. 2011)	G	JA	To define a measure of project complexity	Generic	Quantitative (survey)	Organisational Technological Variety Size Context interdependence

34	(Lebcir & Choudrie 2011)	G	JA	To investigate the factors driving project complexity and their impact	Construction	Quantitative (Simulation)	Size Newness Interconnectivity Uncertainty
35	(Lessard et al. 2014)	M	JA	To conceptualise the complexity and identify associated project features	Infrastructures	Case study	Technical Institutional
36	(Giezen 2012a)	M	JA	To investigate effects of complexity reduction on the planning	Transport	Case study	Political Economic Social Technical
37	(Nguyen et al. 2015)	G	JA	To measure the project complexity	Transport	Quantitative (questionnaire)	Socio-political Environmental Organisational Infrastructural Technological Scope
38	(He et al. 2015)	M	JA	To measure the project complexity	Construction	Quantitative (questionnaire) Case study	Technological Organisational Goal Environmental Cultural Information
39	(Dunović et al. 2014)	M	JA	To explore project complexity	Infrastructures	Qualitative (Interview)	Structural Uncertainty Constraints
40	(Qureshi & Kang 2015)	G	JA	To study organisational factors of project complexity	Generic	Quantitative (questionnaire)	Variety Size Context interdependence

41	(Merrow 2011)	M	B	To study megaprojects	Generic	Case study	Number of factors
42	(Treasury board of Canada secretariat 2009)	G	P	To assess complexity and risk of projects	Generic	Theoretical	Project-Characteristics Strategic-Management Procurement Human Resource Business
43	(Brooks 2013)	M	R	To study megaprojects	Energy	Case study	Number of factors
44	(Mancini 2013)	M	R	To study megaprojects	Generic	Case study	Stakeholders
45	(Locatelli & Littau 2013)	M	R	To study effective delivery of megaprojects	Energy	Quantitative	Number of factors
46	(Littau 2013)	M	R	To explore managing stakeholders in megaprojects	Energy	Quantitative	Number of factors
47	(Flyvbjerg 2014)	M	B	To study megaprojects	Generic	Theoretical	Number of factors
48	(Flyvbjerg et al. 2003)	M	B	To study risk of megaprojects	Transport	Case study	Number of factors
49	(Merrow 2012)	M	JA	To study delivery of megaprojects	Energy	Quantitative	Number of factors
50	(Dimitriou et al. 2012)	M	R	To study megaprojects	Transport	Quantitative Qualitative	Number of factors

[1] M: Megaprojects; G:General; JA: Journal Article; CP: Conference Proceeding; BS: Book Section; B: Book; R:Report; P:Policy;

5.2.2 *Eliciting PCIs*

In this research, the term *Project Complexity Indicator (PCI)* refers to an explicit and clear expression denoting a meaningful degree of complexity as an attribute of a project. A PCI must possess a clear definition that can be easily understood by users. A two-step process is followed to elicit the PCIs:

1. Exploratory search and interpretive analysis;
2. Synthesis and obtaining the final list of PCIs.

These two steps are detailed as follows.

Step 1: Exploratory search and interpretive analysis

An exploratory search is carried out with the sources. More than 300 measures of project complexity have been identified, many having the same or overlapping meanings. After removing the repeating items, a cumulative list of 110 constructs contributing to project complexity were identified. 92 constructs can be directly considered as explicit indicators, such as “number of tasks/activities in project” (Clift & Vandenbosch 1999; Williams 1999; Benbya & McKelvey 2006; Xia & Lee 2004; Bosch-Rekveldt et al. 2011; Vidal et al. 2011).

In contrast, some constructs do not correspond to explicit indicators, therefore needing to be further interpreted to form indicators. For instance, “knowledge, education and/or training”, “technical skills” and “technical capabilities” are mentioned in the literature as constructs of project complexity (Baccarini 1996; Williams 2005; Remington & Pollack 2007; Lane et al. 2002; Geraldi & Adlbrecht 2007; Cooke-Davies et al. 2007) which can be interpreted altogether as “experience with technology”. For those constructs, an interpretive analysis was conducted. Such an analysis has previously been applied in research on project complexity and demonstrated effective results (Bosch-Rekveldt et al. 2011; Vidal et al. 2011; Nguyen et al. 2015). The constructs extracted from the selected sources, together with the results of the interpretive analysis, are shown in the Table 5-3. 18 indicators were identified from this process. Aggregating these new indicators and the explicit indicators leads to a total of 110 indicators. This list needs to be further reviewed to remove possible duplications or overlaps. This is explained in the next section.

Table 5-3: Interpretive analysis of complexity constructs from sources.

Constructs from the sources	Interpreted to
Compatibility of project management tools; variety of tools.	Variety of project management methods and tools
Conflicting goals and objectives; multi-objectivity; diverse objectives.	Diversity of goals and objectives
Diverse perspectives of project owners about the project; stakeholders' views and opinions, judgments, trusts; conflicts of opinions; uncertainty of scope.	Variety of stakeholders' views
Diversity by territory; geographical distribution of suppliers and clients; distance from raw material.	Geographical location of the stakeholders
Interrelatedness/ interdependence of components of products.	Dependencies between tasks
Knowledge, education and/or training; technical skills; technical capabilities.	Experience with technology
New commercial partners, team and/or processes; background of delegates in the organisation.	Experience with parties involved
Obscurity of definition of objectives, goals and business scope	Transparency of objectives
Organisational internal politics; ambiguity and uncertainty within lines of communications.	Relations with permanent organisations
Possibility and effects of changes in macro-organisation or environment external delegates e.g. suppliers, raw materials, exchange rates.	Stability of project environment
Possibility and effects of changes in one product/goal process to other product/goal processes.	Variety of technological dependencies
Possibility and effects of changes in technological/technical aspects of project related to quality or pace; Dynamic environment and changes in information and product specifications.	Scope changing

Size of scope, number of decisions to make, number of deliverables, number of system components, extent of information to analyse	Extent of scope
Technological newness of processes; Technical novelties	Newness of technology
Time conflicts, schedule overlapping, intercepting time plans	Schedule conflicts
Transparency of commutations among external teams or delegates e.g. contractors, clients; personal characteristics improving collaboration e.g. empathy.	Trust in contractors
Transparency of commutations among team members; personal characteristics improving collaboration e.g. empathy.	Trust in team
Competitions; Shortfall in demand in destination market.	Market competition

Step 2: Synthesis to obtain the final list of PCIs

This research uses a spreadsheet; indicators similar in meanings are positioned together. Three actions are then defined to synthesise the indicators.

- "Title Change (TC)" for those indicators which are appropriate as a final PCI in meaning but their title is not clear or explicit;
- "Merge (M)" for those indicators with the same or similar meaning;
- Some indicators do not require any of the above actions; they are marked as "None of above two actions (NA)".

Table 5-4 presents the result of the synthetic review. It shows that this process led to a reduction of the list of PCIs, thereby finally obtaining 51 indicators.

Table 5-4: Synthetic review of indicators to obtain final PCIs

	Indicators	Action	Final PCIs
1	Changing economy	NA	Changing economy
2	Level of market competition	TC	Market competition
3	Market unpredictability and uncertainty	NA	Market unpredictability and uncertainty
4	Stability of project environment	M	Stability of project environment
5	Dependencies with the environment		
6	Technological dependencies with the environment	TC	Interaction between the technology system and external environment
7	Local laws and regulations	NA	Local laws and regulations
8	Level of political influence	TC	Political influence
9	Cultural diversity	M	Cultural configuration and variety
10	Cultural variety		
11	Cultural differences	NA	Cultural differences
12	Public agenda	TC	Significance on public agenda
13	Size of capital investment	TC	Size of capital investment
14	Diversity of investment and funding resources	M	Variety of investors and financial resources

15	Number of investors and financial resources		
16	Contract types	NA	Contract types
17	Institutional configuration	M	Variety of institutional configuration
18	Number of departments involved		
19	Number of hierarchical levels		
20	Stakeholders interrelations		
21	Number of different disciplines, norms and standards		
22	Number of interfaces in the project organisation		
23	Variety of Disciplines, norms, standards		
24	Organisation internal support	M	Support from permanent organisations
25	Relations with permanent organisations		
26	Organisation internal support		
27	Variety of hierarchical levels within the organisation		
28	Team cooperation and communication	NA	Team cooperation and communication
29	Availability of people due to sharing	TC	Availability of human resources
30	Trust in contractors	M	Level of trust (inter/intra teams)
31	Trust in project teams		
32	Cultural diversity	M	Diversity of participants
33	Number of groups/teams to be coordinated		
34	Staff quantity		
35	Variety of different nationalities		
36	Number of stakeholders		
37	Stakeholders network size		
38	Dynamic and evolving team structure	M	Dynamic and evolving team structure
39	Change in team structure		

40	Experience with parties involved	M	Experience and capabilities within teams
41	Diversity of staff background		
42	Variety of organisational skills needed		
43	Variety of stakeholders interest and perspective	TC	Interest and perspectives among stakeholders
44	Interdependency of physical resources	TC	Resource and raw material interdependencies
45	Number of companies/ projects sharing their resources	M	Variety of resources
46	Variety of resources		
47	Availability of physical resources due to sharing	NA	Availability of physical resources
48	Availability of information	M	Availability of information
49	Degree of obtaining information		
50	Number of information systems		
51	Integration of more than one information system or platform		
52	Reliability of sources	M	Reliability of information platforms
53	Reliability of information platforms		
54	Interdependence of information systems	NA	Interdependence of information systems
55	Degree of processing information	M	Level of processing and transferring information
56	Capacity of transferring information		
57	Geographical location of the stakeholders	M	Diversity of sites and locations
58	Combined transportation		
59	Interdependence between sites, department and companies		
60	Multiple participating countries		
61	Number of different languages		
62	Number of different nationalities		
63	Number of locations		
64	Process interdependence	M	Process interdependencies

65	Levels of interrelation between phases		
66	Technological process dependencies		
67	Interrelations between technical processes		
68	Dependencies between tasks	M	Dependencies between tasks
69	Interconnectivity and feedback loops in the task and project networks		
70	Variety of product components	M	Number of activities
71	Number of tasks and activities		
72	Task delivery uncertainty	M	Unpredictability of tasks
73	Unpredictability of tasks		
74	Number of decisions to be made		
75	Variety of solutions/paths/path-goal	M	Diversity of activities elements
76	Diversity of task elements		
77	Duration of project	NA	Duration of project
78	Dependencies between schedules	NA	Dependencies between schedules
79	Time pressure	M	Intensity of project schedule
80	Schedule conflicts		
81	Intensity of project duration		
82	Project urgency		
83	Uncertainty of the project management methods and tools	M	Applicability of project management methods and tools
84	Applicability of project management methods and tools		
85	Variety of project management methods and tools	NA	Variety of project management methods and tools
86	Number of goals and objectives	M	Variety of goals and objectives
87	Variety of goals and objectives		
88	Interdependence of objectives	NA	Interdependence of objectives
89	Goal alignment	M	Transparency of objectives
90	Transparency of objectives		
91	Uncertainty of goals		

92	Goals/Product specifications transparency		
93	Scope changing	NA	Scope changing
94	Demand of creativity	M	Level of innovation
95	Organisational degree of innovation		
96	Technological degree of innovation		
97	Variety of technological skills needed	M	Technological experience and capabilities
98	Experience with technology		
99	Repetitiveness of processes	M	Repetitiveness of process
100	Newness of technology		
101	Interdependence between the components of the product	M	Specifications interdependencies
102	Interdependence between actors		
103	Specifications interdependencies		
104	Variety of technological dependencies	M	Technological varieties
105	Technological process dependencies		
106	Variety of the technologies used during the project		
107	Number of system components	M	Variety of system components
108	Extent of scope		
109	Variety of product components		
110	Changing technology	NA	Changing technology
M: Merge; TC: Title Change; NA: No Action.			

5.3 Establishing a taxonomy of PCIs

5.3.1 *Constructing the taxonomy of PCIs*

While categorisation, grouping, classification and typology have been used interchangeably for determining aspects of project complexity, and have sometimes caused confusion, taxonomy has not appeared in literature as a distinct term. Marradi (1990) specified taxonomy as “when several fundamental divisions are ordered in succession, rather than simultaneously … taxonomy is also derived from the source of a phenomenon". In management research, taxonomy is defined as a semantic classification which organises a large number of related concepts into a logical hierarchy (Krishnaswamy & Sivakumar 2009). Examples of taxonomy oriented research in project management include Sun & Meng (2009), Benjelloun et al. (2010), Nijhuis et al. (2015), Alharbi et al. (2015) and Kian M.R & Sun (2014).

Establishing a taxonomy of PCIs is also essential for the next step of the PCA development process, which involves establishing a weight for each indicator, by using the AHP method. Indeed, it is not feasible to conduct pairwise comparisons with 51 indicators altogether (2,550 comparisons would have to be conducted); nor is it meaningful to compare completely unrelated indicators. The development of the taxonomy allows comparisons to be conducted between fewer and related indicators within sub-categories, and between those sub-categories.

The process of constructing the taxonomy of PCIs consists of two interactive and iterative procedures:

- A top-down method to determine the higher levels of hierarchy, which should be general and holistic; and

- A bottom-up method to obtain the lower levels of hierarchy, which should be objective and measurable.

The two procedures interact with one another, as the outputs of one may contribute to the other. Figure 5-2 shows the process of developing the taxonomy.

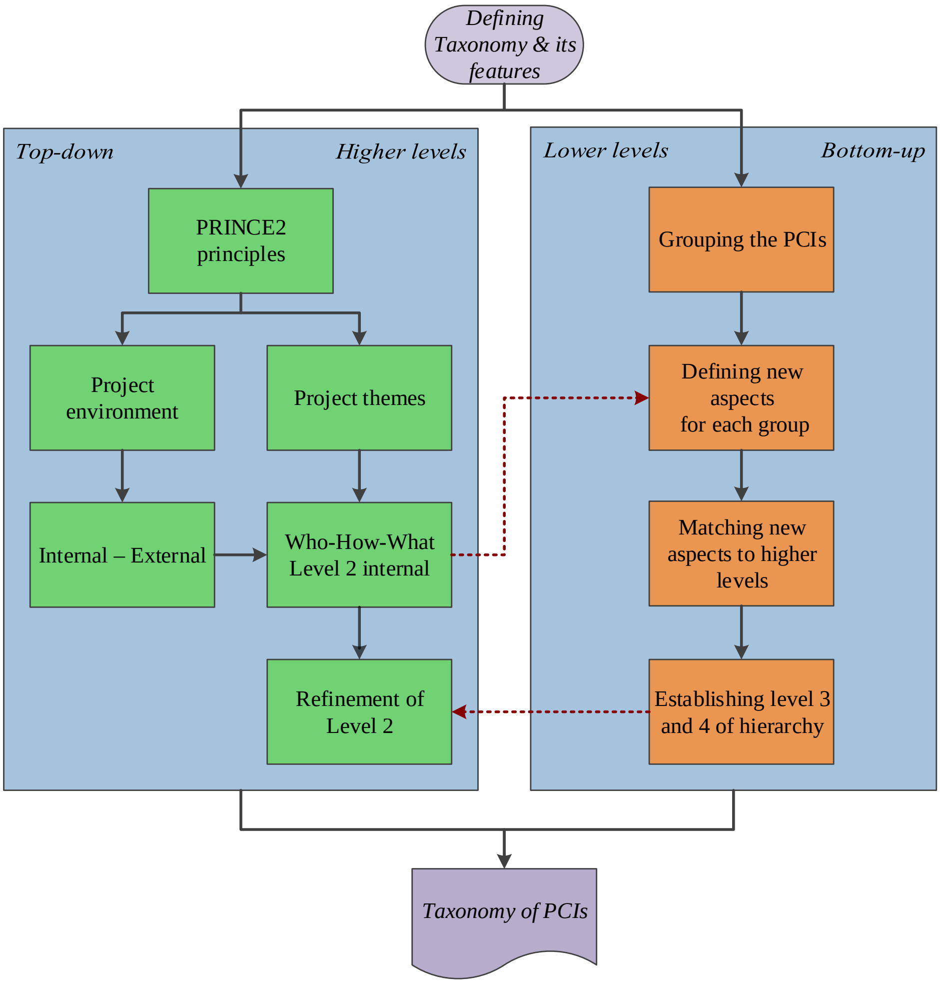


Figure 5-2: Process of constructing taxonomy of PCIs

Determining the higher levels categories of the taxonomy

PRINCE2 (PRojects IN Controlled Environments) is a structured, non-proprietary and generic project management tool. PRINCE2 is a de facto standard which is used extensively in the public and private sectors, both in the UK and internationally (Office of Government Commerce 2009). It is used as the basis to determine the higher level categories of the taxonomy. PRINCE2 identifies two main fundamentals as the basis of any project: "project environment" and "project themes":

(1) Project environment is the environment within which the project is carried out; it includes the physical environment such as air, water and other land resources, as well as humans and their interactions both with and within project (Kohli 2006). Regarding the project environment, PRINCE2 states that *"the project team should consider the project in its cultural, social, international, political and*

physical environmental contexts". By these meanings, project environment can be divided into two major sub-divisions: external and internal.

a. External environment includes those aspects of a project which are outside the direct control of the project delivery organisation and which relate to external stakeholders, such as governments or market forces.

b. Internal environment, in contrast, involves those elements that are actually within the control of the project management team.

Project complexity is an inherent attribute of any project (descriptive approach). Therefore, aspects of project complexity can also be grouped into external and internal. Thus the first level of hierarchy can be branched into internal and external.

(2) Project themes describe the facets of project management that must be addressed continually. PRINCE2 considers seven main themes for projects and associates each theme with a question (Table 5-5). However looking at the description of themes, they can be clustered in three main terms of the "what", the "who" and the "how" of the project (Bosch-Rekveldt et al. 2011) (see Table 5-5):

- The "what?" of the project involves content, characteristics of product to be delivered and the objectives of a project. The business idea of a project can be embedded in "What?" as it describes the early motivation behind a project, which denotes the project's goals.

- The "who?" of the project refers to the parties involved, associated organisations and project sponsors that contribute by any means to the delivery of the project. They may include stakeholders, other people, and resources.

- The "how?" of the project involves the execution process, activities, information, time issues and all required means to deliver the project.

"Cross-cluster" is defined as relating to change and risk themes. As discussed in Chapter 2 of this study, risk, uncertainty and changes (and associated consequences) are contributing elements to project complexity, yet are not the sources of complexity; therefore they are not categorised as a separate cluster. However, their associated PCIs may appear across the “what?”, “who?” and “how?” clusters.

Table 5-5: Overview of project themes and clusters

<table>
<tr><th>Theme</th><th>Description</th><th>Question</th><th colspan="2">Defined Clusters</th></tr>
<tr><td>Organisation</td><td>Project sponsors, project team and all associated organisations</td><td>Who?</td><td>Who?</td><td>Stakeholders
Resources
People</td></tr>
<tr><td>Business case</td><td>An idea developed into a viable investment proposal for the organisation.</td><td>Why?
Business reason?</td><td rowspan="2">What?</td><td rowspan="2">Objectives
Product characteristics</td></tr>
<tr><td>Quality</td><td>The quality attributes of product to be delivered, features of project goals</td><td>What?</td></tr>
<tr><td>Plans</td><td>The series of approved plans which the project proceeds upon.</td><td>How?
How much?
When?</td><td rowspan="2">How?</td><td rowspan="2">Process means
Information
Activities
Time</td></tr>
<tr><td>Progress</td><td>Monitoring the progress and performance.</td><td>Where are we now?
Where are we going?
Should we carry on?</td></tr>
<tr><td>Change</td><td>Anticipation of potential impacts of requested changes.</td><td>What’s the impact?</td><td colspan="2" rowspan="2">Cross- Clusters</td></tr>
<tr><td>Risk</td><td>Uncertainty in plans and project environment.</td><td>What if?</td></tr>
</table>

As a result, the identified three clusters of project themes constitute the second level of the hierarchy, corresponding to the internal category. The external environment of projects seems independent from those “what?”, “who?” and “how?” themes and is mostly related to society, the economy, politics, market, regulations and environment. Therefore, the second hierarchy level for the external category is defined via a bottom-up approach.

Determining the lower levels of the taxonomy

Grouping and interpreting

Similar PCIs are grouped together. The main criterion to group PCIs is similarity of their interpretation in the context of project complexity. The source of each PCI is explored to highlight its specific meaning and the situation where it is applied. Then for each group, based on the collective connotation of its members (PCIs), a generic title is defined, which in fact is a new aspect of project complexity in level 3 of the hierarchy for internal and level 2 for external categories. The outcomes of the grouping exercise are explained below:

- *Economy:* The three indicators that identified the "economy" aspect are "changing economy", "market competition" and "market unpredictability and uncertainty". The PCIs entail characteristics of project complexity derived from sources such as "economy" (Giezen 2012b), "finance" (Gransberg et al. 2012; Whitty & Maylor 2009), "ambiguity and uncertainty" (Sommer & Loch 2004; Geraldi et al. 2011; Williams 2002), "directional" and "structural" complexity (Remington & Pollack 2007). Therefore "economy" here denotes those aspects of project complexity which are related to elements of an economic system consisting of the production, distribution, trade, market and actors of economy, including competitors in a given geographical location.

- *Environment:* by considering the definition of project environment presented in section 5.3.2, PCIs of "stability of project environment" and "interaction between the technology system and external environment" refer to complexity aspects of external "environment" – as a new aspect – of project including "interaction" (Geraldi & Adlbrecht 2007), "context" (Vidal et al. 2011; Qureshi & Kang 2015) and "stability" (Jiang et al. 2008; Jaafari 2003; Bosch-Rekveldt & Mooi 2008; Bosch-Rekveldt et al. 2011).

- *Laws and regulations*: A regulation is defined as a legal norm intended to shape imperfections (Mendoza 2015) and it usually is legalised by superior authorities. The "local laws and regulations" PCI involves the complexity of "context", "constraints" (Dunović et al. 2014) and "array" (Shenhar & Dvir

2007). It defines the project complexity issues which are caused by regulations external to the project.

- *Politics*: refers to achieving and governing a human community (usually a state or country) by organised control. Political complexity is often demonstrated by unexpected changes or the emergence of new parties or even governments. Among PCIs, the “political influence” identifies issues relevant to external complexity which involve aspects of project complexity such as “politics” (Whitty & Maylor 2009; Geraldi et al. 2011; Giezen 2012a), “stakeholders” (Remington & Pollack 2007) and “faith” (Geraldi & Adlbrecht 2007).

- *Society*: is another essential element of the external environment of a project. “Cultural configuration and variety”, “cultural differences” and “significance of the public agenda” all denote a concept of project complexity as “society”. These PCIs comprise “cultural” (Brockmann & Girmscheid 2007; He et al. 2015) and “social” (Brockmann & Girmscheid 2007; Cooke-Davies et al. 2007) aspects of complexity.

- *Capital resources*: “size of capital investment” and “variety of investors and financial resources” are two PCIs that each address “capital resources” complexity. These PCIs are related to aspects of complexity from sources such as complexity of “capital”, “variety”, “interaction” and “size” (Clift & Vandenbosch 1999; Vidal et al. 2011; Lebcir & Choudrie 2011; Qureshi & Kang 2015). The capital resources of a project are those concerned with the long-term financing of and investment in infrastructure and industrial projects, based upon the feasibility studies.

- *Discipline*: “contract types”, “variety of institutional configuration”, “support from permanent organisations” and “team cooperation and communication” are grouped together, as they all denote a concept of organisational “discipline”. The PCIs also address complexity aspects of “array”, “context”, “cultural”, “environmental”, “faith”, “interfaces”, “managerial” (Shafiei-Monfared & Jenab 2012a), “organisational” (Baccarini 1996; Benbya & McKelvey 2006), “structural” (Austin et al. 2002; Williams 1999; Maylor et al. 2008; Jiang et al. 2009), “institutional” (Lessard et al. 2014).

Organisational discipline is the orderly and systematic directing of the of the organisation's businesses by its staff, that strictly adhere to the crucial rules and regulations.

- *People*: "availability of human resources", "level of trust (inter/intra teams)", "diversity of participants", "dynamic and evolving team structure", "experience and capabilities within teams", and "interest and perspectives among stakeholders" are grouped together, based on the idea that all of them describe concepts of project complexity specifically related to teams working in, or stakeholders of, a project. In a broader view, each of them represents an indicator of project complexity related to the "people's" aspect of a project. The PCIs in this group also consist of complexity aspects such as "constraints", "faith", "dynamic" (Benbya & McKelvey 2006; Maylor et al. 2008; Geraldi et al. 2011), "work practice" (Remington et al. 2009), "variety", "stakeholders", "organisational" and "institutional".

- *Physical resources*: "availability of physical resources", "resource and raw material interdependencies" and "variety of resources" are grouped together and denote "physical resources" as a new aspect of project complexity. PCIs in this group also highlight concepts of project complexity such as "constraints", "resources", "infrastructural" (Nguyen et al. 2015), and "variety". Physical resources involve the man-made resources, such as buildings, technology, and any products or natural resources necessary for the execution of a project.

- *Information:* the four PCIs of "availability of information", "reliability of information platforms", "interdependence of information systems", and "level of processing and transferring information" are similar in their meanings and application which focus on "information". They consist of "directional", "constraints", "information" (He et al. 2015), "infrastructural", "interdependence", "interfaces", "size", "system" (Shenhar & Dvir 2007) and "ambiguity" aspects of project complexity. "Information" refers to those facts and data provided or learned about a project, which must be accurate and timely, as well as specific within a context. Information must lead to enhancing understanding and decreasing the uncertainty of a project.

Information systems are those structures designed to collect, store, distribute, or even engage in the destruction of, information.

- *Tasks:* “dependencies between tasks”, “number of activities”, “unpredictability of tasks”, “diversity of activities elements” and “process interdependencies” are PCIs which perceptibly deliberate the project complexity of “tasks”. “Diversity of sites and locations” is initially constructed based upon the synthesis of a number of other complexity factors such as geographical locations of the stakeholders, combined types of transportation, or multiple participating countries in the project, as explained in section 5.2.2 of this chapter. It emerged that these factors cause difficulties and uncertainties of performing project activities (Lu et al. 2014; Clift & Vandenbosch 1999; Vidal & Marle 2008). Therefore “diversity of sites and locations” can be considered within the “tasks” complexity group. A number of aspects are mentioned in sources about PCIs in this group; for instance “variety”, “interdependence”, “interconnectivity” (Lebcir & Choudrie 2011), “interfaces”, “size”, “task” (Brockmann & Girmscheid 2007; Lu et al. 2014), “uncertainty” and “organisational” complexity. A task in project context is an activity that must be accomplished within a definite period of time to achieve certain goals through defined processes.

- *Time:* “duration of project”, “dependencies between schedules” and “intensity of project schedule” are PCIs which are combined and the new “time” aspect of project complexity. These PCIs also reflect the concepts of theoretical project complexity gained from the reviewed literature such as “constraints”, “interaction”, “interdependence”, “interfaces”, “schedule” (Gransberg et al. 2012), “pace” (Geraldi et al. 2011), “scope”, “size” and “time” (Remington et al. 2009). Time in a project regards a project’s milestones, task durations, and planned start and finish dates. It also tightly interacts with resource and budget allocation, and dependencies.

- *Tools and methods:* “applicability of project management methods and tools” and “variety of project management methods and tools” clearly centred on the project management “tools and methods” aspect of complexity. From their sources, aspects such as “context”, “infrastructural”, “institutional”, "interfaces", "managerial", "organisational" and "variety" project complexity are also identified. Tools or methods in project management are used to aid the execution of challenging and complex responsibilities such as scheduling, resource and cost planning, and risk management.

- *Objectives:* "variety of goals and objectives", "interdependence of objectives", "transparency of objectives", and "scope changing" are grouped together and highlight the characteristics of a new "objectives" related aspect of project complexity. In addition, they involve "ambiguity", "context", "fact" (Geraldi & Adlbrecht 2007), "goals" (Remington & Pollack 2007), "interdependence", "scope", "temporal", "uncertainty" and "variety" as aspects of project complexity cited in the literature. Project objectives are statements that describe what the project must accomplish, or the business value the project wishes to attain and must be specific, tangible and deliverable.

- *Technical:* "level of innovation", "technological experience and capabilities", "repetitiveness of process", "specifications interdependencies", "technological varieties", "variety of system components" and "changing technology" are seven PCIs that form a group which entails aspects of project complexity such as "work practices", "dynamic", "interdependence", "novelty" (Lebcir & Choudrie 2011), "size", "system", "technological" (Baccarini 1996; Clift & Vandenbosch 1999; Vidal et al. 2011), "temporal", "uncertainty" and "variety". A deeper look at the interpretation of all these aspects leads to the definition of a new aspect of "technical" project complexity. "Technical" here refers mostly to product specifications of a project and its dedicated characteristics.

Matching the new aspects to higher levels

In this stage, the new identified aspects in the lower levels are matched and linked into the higher levels to fully establish the hierarchy. The first five groups: "society", "politics", "economy", "environment" and "law & regulations" are independent of any project; they are external factors. Therefore, they can be considered as "sub-categories" at level 2 of external complexity. Figure 5-3 presents the structure of hierarchy in *external* category at level 1 and 2.

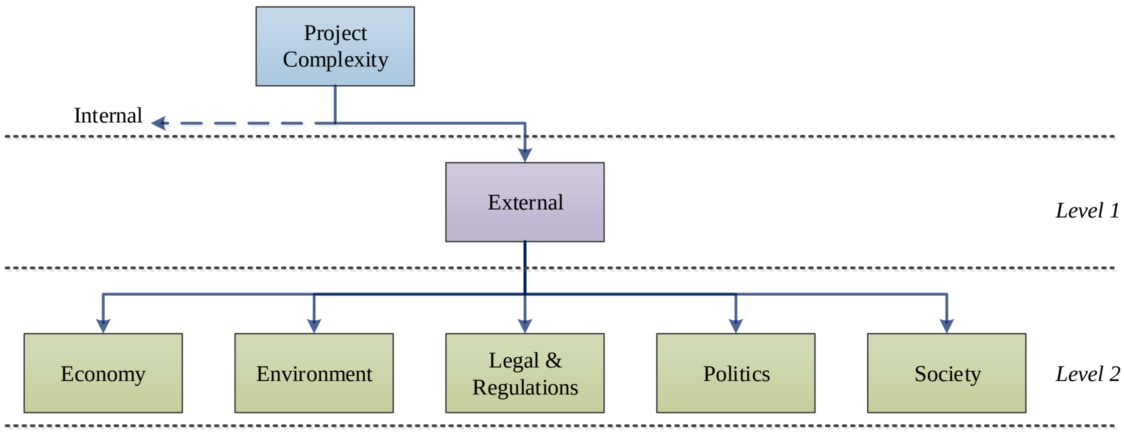


Figure 5-3: Structure of external category at levels 1 & 2

The remaining 10 groups are different aspects of a project; they are internal indicators. They need to be matched with the "who?, how? and what?" project themes at the level 2 of the hierarchy. The "who?" of a project generally signifies project sponsors and delegations such as project teams or organisations and contractors. From the other side, among all new defined aspects, *discipline* and *people* seem directly linked to the "who?", clearly indicating aspects of a project team. Resources are also considered as sponsors of a project in which they supply the needs of that project. With this definition, *capital* and *physical resources* are considered to be part of the "who?" of a project. The "how?" of a project describes execution process, activities, information, schedules and all required means to deliver that project. By this definition *information*, *tasks*, *time* and *tools and methods* match the "how?" of the project. The "what?" of the project takes into content, characteristics of product to be delivered or goals and objectives. Consequently the last two new aspects of *objectives* and *technical* are acknowledged as being linked to "what?". Figure 5-4 shows the structure of levels 1, 2 and 3 for the *internal* category.

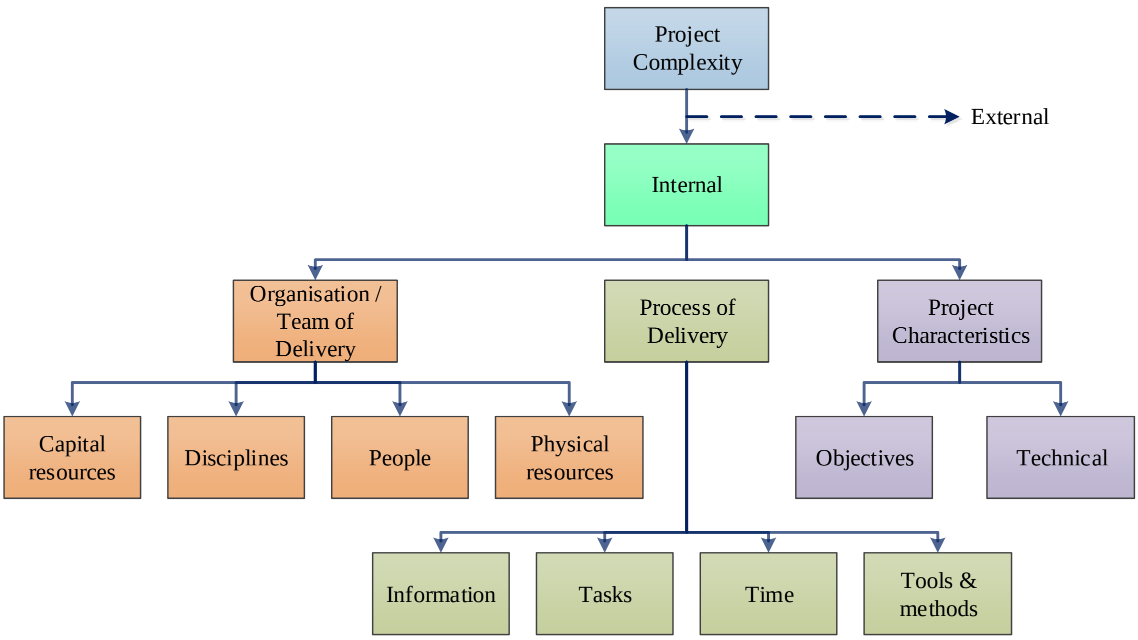


Figure 5-4: Constituted structure of internal category levels 1 & 2 & 3

5.3.2 *Taxonomy of PCIs*

Table 5-6 and Table 5-7 present the final taxonomy of external and internal indicators including hierarchy levels 3 and 4 respectively, containing the actual PCIs. For easier reference, a code is allocated to each PCI that captures the level and category it belongs to.

Table 5-6: Taxonomy of PCIs - external category

LEVEL 1	LEVEL 2	LEVEL 3	Code
External (E)	Economy (EC)	Changing economy	EEC1
		Market competition	EEC2
		Market unpredictability and uncertainty	EEC3
	Environment (EN)	Stability of project environment	EEN1
		Interaction between the technology system and external environment	EEN2
	Legal & regulations (LE)	Local laws and regulations	ELE1
	Politics (PO)	Political influence	EPO1
	Society (SO)	Cultural configuration and variety	ESO1
		Cultural differences	ESO2
		Significance on public agenda	ESO3

Table 5-7: Taxonomy of PCIs - Internal category

LEVEL 1	LEVEL 2	LEVEL 3	LEVEL 4	Code
Internal (I)	Organisation / Team of Delivery (OR)	Capital resources (CA)	Size of capital investment	IORCA1
			Variety of investors and financial resources	IORCA2
		Disciplines (DI)	Contract types	IORDI1
			Variety of institutional configuration	IORDI2
			Support from permanent organisations	IORDI3
			Team cooperation and communication	IORDI4
		People (PE)	Availability of human resources	IORPE1
			Level of trust (inter/intra teams)	IORPE2
			Diversity of participants	IORPE3
			Dynamic and evolving team structure	IORPE4
			Experience and capabilities within teams	IORPE5
			Interest and perspectives among stakeholders	IORPE6
		Physical resources (PH)	Resource and raw material interdependencies	IORPH1
			Variety of resources	IORPH2
			Availability of physical resources	IORPH3
	Process of Delivery (PR)	Information (IN)	Availability of information	IPRIN1
			Reliability of information platforms	IPRIN2

			Interdependence of information systems	IPRIN3
			Level of processing and transferring information	IPRIN4
		Tasks (TA)	Diversity of sites and locations	IPRTA1
			Process interdependencies	IPRTA2
			Dependencies between tasks	IPRTA3
			Number of activities	IPRTA4
			Unpredictability of tasks	IPRTA5
			Diversity of activities elements	IPRTA6
		Time (TI)	Duration of project	IPRTI1
			Dependencies between schedules	IPRTI2
			Intensity of project schedule	IPRTI3
		Tools & methods (TO)	Applicability of project management methods and tools	IPRTO1
			Variety of project management methods and tools	IPRTO2
	Project Characteristics (PC)	Objectives (OB)	Variety of goals and objectives	IPCOB1
			Interdependence of objectives	IPCOB2
			Transparency of objectives	IPCOB3
			Scope changing	IPCOB4
		Technical (TE)	Level of innovation	IPCTE1
			Technological experience and capabilities	IPCTE2

			Repetitiveness of process	IPCTE3
			Specifications interdependencies	IPCTE4
			Technological varieties	IPCTE5
			Variety of system components	IPCTE6
			Changing technology	IPCTE7

5.4 Chapter summary

This chapter has presented the development of the taxonomy of PCIs in two main steps. The first step identified a list of 51 PCIs through a comprehensive literature review and synthesis. The second step established the taxonomy, which provides a logical hierarchy for these 51 indicators. The structure of the taxonomy follows the principles of PRINCE2; this will facilitate its acceptance by project management professionals. These PCIs define the facets that need to be measured when assessing the complexity of an energy megaproject. However, each of these PCIs may not carry the same weight during the assessment. Determining the appropriate weight for each of them is addressed in the next Chapter.

Chapter 6 Establishing Weights for Project Complexity Indicators

6.1 Introduction

This chapter aims to establish weights of all PCIs during project complexity assessment, using an integrated Delphi-AHP method. The task is carried out in four main steps, each explained in one section of the chapter:

(1) Identifying and selecting the most appropriate experts for the GDM panel (Section 6.2);

(2) Delphi-AHP round 1, to prioritise the PCIs and ensuring consistency of experts' judgments (Section 6.3);

(3) Delphi-AHP round 2, to build the required level of consensus (Section 6.4);

(4) Eliciting the local and global weights of the PCIs, based on three different scenarios of expert's weighting and analysis of the results (Section 6.5).

6.2 Selecting experts

Okoli & Pawlowski (2004) provided detailed guidelines on expert selection for a Delphi study. A Delphi study is a group decision procedure that requires qualified experts who have a deep understanding of the problem or issue in question. Therefore, the search and selection of the most suitable experts is crucial for its successful implementation

The size and structure of the panel normally depend on the nature of the research question and objectives. This study involves two relevant types of experts, who have significant and valuable knowledge about the energy sector and megaprojects: academics and professionals. Normally there will be 10 to 18 people in each panel. To identify and select the experts, this study adopted a multi-stage process based on the guidelines cited above. The process of selecting experts is outlined in Figure 6-1.

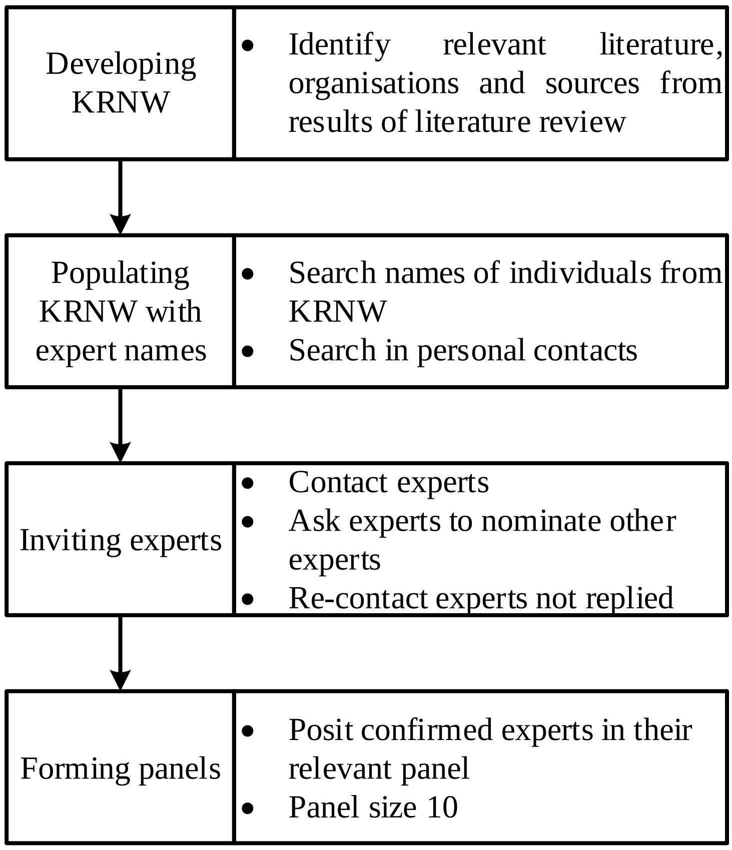


Figure 6-1: Process of selecting experts

In the first stage, a Knowledge Resource Nomination Worksheet (KRNW) has been developed to help classify the experts before selecting them, in order to avoid neglecting any important category of experts. For this task, the publications identified in the earlier literature review provide information on individual authors, as well as their organisations; such as SAID Business School, European Cooperation in Science and Technology (COST) megaprojects action, and large energy companies. That information enabled the identification of 78 potential candidate experts for the Delphi study. The list of experts was reviewed to ensure all candidates possessed the needed levels of familiarity with megaprojects and the energy sector.

All the identified experts were then contacted via email and invited to participate in the Delphi-AHP process, with explanation about their roles and expected contributions. They were provided with information about this study, including a brief research background. If experts were not able to participate, they were asked to nominate other relevant experts. A follow-up email was sent to remind those experts who had not responded to the first invitation. Appendix 1 presents a sample of the invitation letter, profile and research background. The round 1 Delphi-AHP questionnaire was also sent to the experts with the invitation email. The aim was to avoid loss of interest by experts due to delay in different rounds of communication, which is a known weakness of the Delphi method.

The invitation led to 21 experts agreeing to participate in the study. They were ranked based on their experience and familiarity with the subjects of this research; the lowest ranked candidate was not included in this study. This produced two panels of academics and professionals, with 10 members in each panel. Table 6-1 summarises the background information of the experts. 50% of academics and 70% of professionals have more than 16 years of experience in the energy sector. Also 60% of the panel members have at least advanced knowledge about megaprojects.

Table 6-1: Summary of the background information on the experts

1) Experience in energy sector					
Years	6-10	11-15	16-20	>20	
Academia	2	3	3	2	
Professional	2	1	3	4	
2) Sub-Sector of professionals					
Sector	Oil&Gas	Renewable	Utility	Consultancy	Construction
Professional	3	2	1	1	3
3) Level of experience in megaprojects					
Level	Familiar	Knowledgeable	Advanced	Expert	
Academia	0	5	3	2	
Professional	0	2	3	5	

6.3 Delphi-AHP round 1 (Consistency checking)

The aim of the Delphi-AHP round 1 is to elicit the PCI weights through sets of AHP pair-wise judgment matrices, and to achieve consistency of judgments from each expert (see Figure 6-2).

.

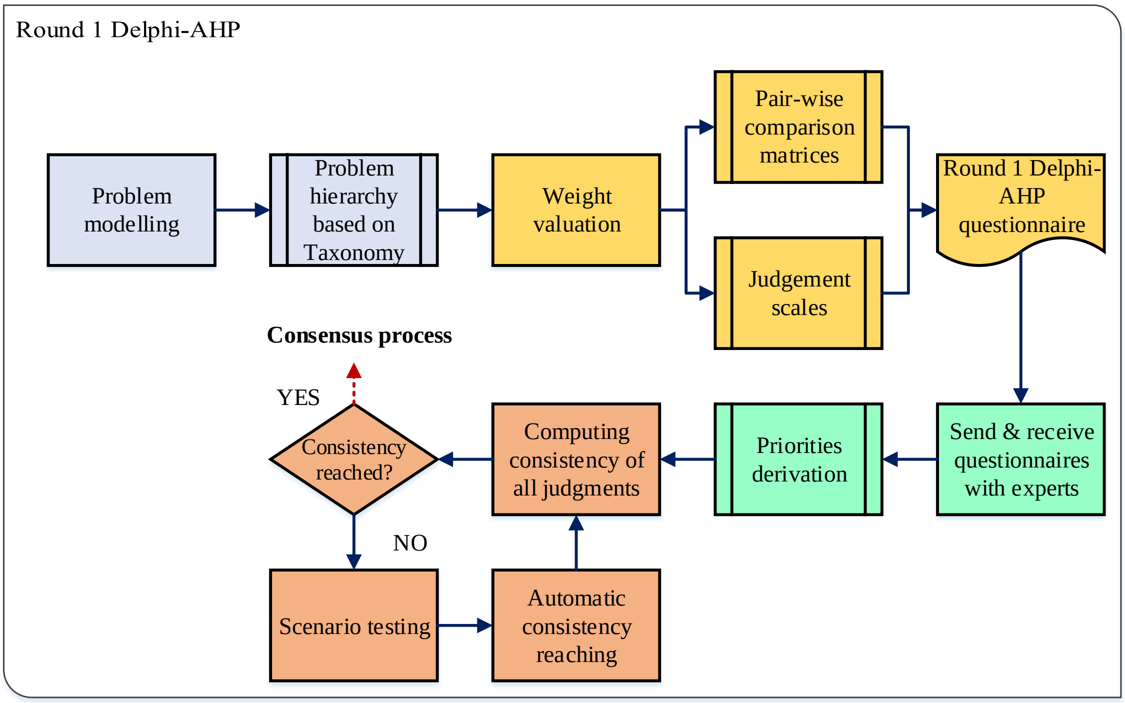


Figure 6-2: Round 1 Delphi- AHP process

6.3.1 *Structuring the AHP model hierarchy*

In the AHP, the problem must be presented in a hierarchical structure. This structure is important because different structures may result in different final weights. Since the PCIs have already been structured in a taxonomy hierarchy, that structure can be used. An AHP hierarchical structure is built according to Figure 6-3. The weights should be computed for the items located at the lowest levels (leafs) of the taxonomy. First tier criteria (intermediate goals) correspond to the 10 sub-categories of internal and 5 sub-categories of external project complexity. However, the external category only comprises 10 PCIs and it is more practical to obtain the priorities of all PCIs with one matrix; then weights of corresponding categories can be computed by aggregating the weights of associated PCIs. Second tier criteria (alternatives) correspond to 10 external and 41 internal PCIs. Structuring the AHP model hierarchy allows the performing of the weight valuation process and designing the round 1 questionnaire. In total 12 matrices were created, indicated as M1, M2 … M12 in Figure 6-3.

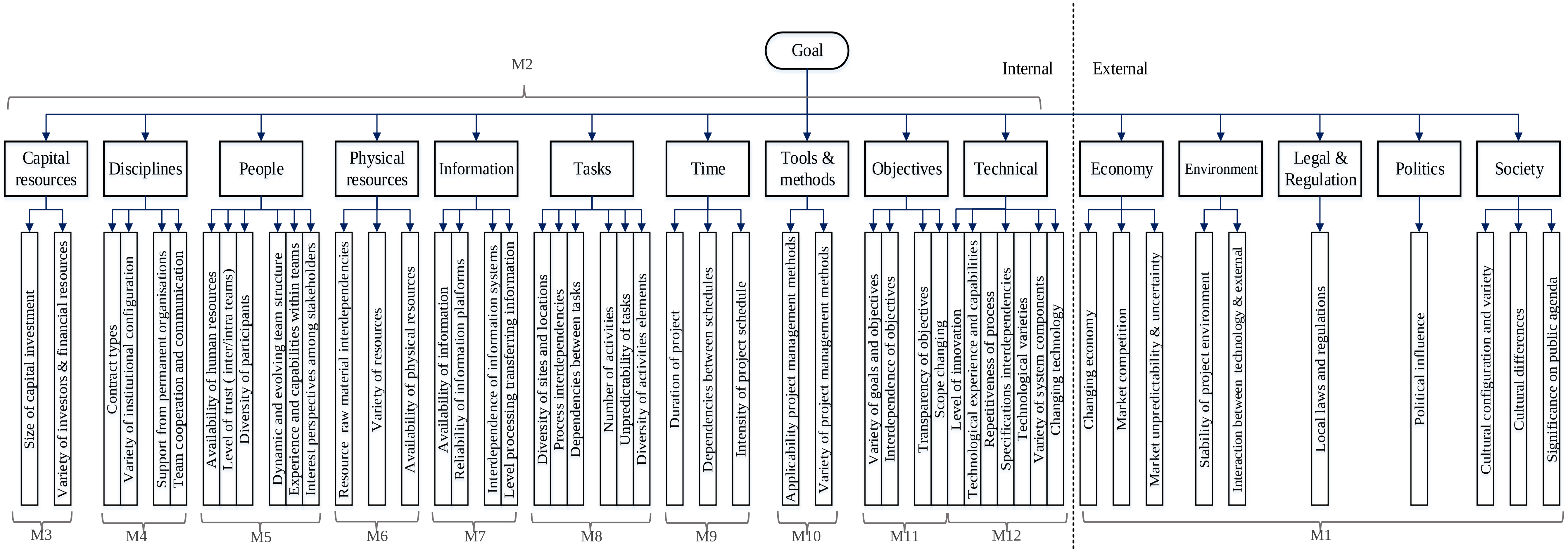


Figure 6-3: AHP model hierarchy

6.3.2 *Providing weight valuation matrices*

Each expert's contribution is collected using a questionnaire. To design the questionnaire, based on the process of AHP, two main tasks are performed: identifying judgement scales and conducting pair-wise comparisons. The linear scale, with the integers one to nine and their reciprocal verbal scales, was used in this research. All pair-wise judgments of all alternatives are logged in a positive reciprocal matrix, called the Pair-wise Comparison Matrix (PCM), where a_{ij} stands for the pair-wise judgment value between alternatives *i* and *j*. An expert is asked to enter his/her relative judgments for all pairs of alternatives in a cell matrix based on the judgment scales (Table 4-2). For example, if PCI *i* is "Slightly more important or preferred" than PCI *j*, then the value '3' is entered in the judgement matrix; or if considering *j* against *i*, then the value '1/3' is entered. The comparison values are then used to elicit the weights of indicators and categories.

Comparisons at tier 2 provide the weights of categories for internal indicators. In the external category, there are only 10 indicators within 5 categories at tier 2, and three of the categories (politics, law & regulations and environment) have only one or two indicators. Therefore, it is more effective to carry out the comparisons among all 10 indicators in one matrix rather than five matrices at tier 2. Weights of categories can subsequently be calculated by aggregating individual weights of indicators in that specific category. This reduces the time needed for calculations and enhances the efficiency of the method. Therefore, the model hierarchy established in the previous section leads to twelve matrices: one matrix of external indicators and ten matrices of internal indicators at tier 2, and one matrix of internal indicators at tier 1 (Table 6-2). These twelve matrices are included in the round 1 questionnaire (Appendix 2) and were sent to the selected panel experts. Experts were asked to conduct the comparisons based on their cumulative knowledge/expertise rather than any specific project. Table 6-3 shows an example of a completed matrix used for the internal category of "People" (tier 2). At the end of this stage, 12 sets of tables are collected from each of the 20 experts.

Table 6-2: Matrices used in the Delphi-AHP process

Name of matrix	Size of matrix
M1-External indicators – Tier 2 external	10
M2-Internal sub-categories – Tier 1	10
M3-Capital resources - Tier 2 of internal	2
M4-Disciplines - Tier 2 of internal	4
M5-People - Tier 2 of internal	6
M6-Physical resources - Tier 2 of internal	3
M7-Information - Tier 2 of internal	4
M8-Tasks - Tier 2 of internal	6
M9-Time - Tier 2 of internal	3
M10-Tools & Methods - Tier 2 of internal	2
M11-Objectives - Tier 2 of internal	4
M12-Technical - Tier 2 of internal	7

Table 6-3: Sample of AHP pairwise comparison matrix in round 1 Delphi-AHP, sub-category of "people"

	A	**B**	**C**	**D**	**E**	**F**
Availability of human resources (A)		1/3	3	5	1/7	1/5
Level of trust (inter/intra teams) (B)			5	3	1/5	1/3
Diversity of participants (C)				1/3	1/7	1/5
Dynamic and evolving team structure (D)					1/7	1/3
Experience and capabilities within teams (E)						5
Interest and perspectives among stakeholders (F)						

6.3.3 *Consistency checking*

In the process of GDM, consensus between experts is usually obtained using the basic rationality values that each expert expresses. Thus, consistency checking should be first applied to test the rationality of each expert's judgments. The aim of this process is to identify inconsistencies and contradictions with an expert's judgement and to recommend corrections. As discussed in chapter 4, the integrated method of consistency-checking and consensus-building developed by Chiclana et al. (2008) is applied here. Consistency-checking in this method is based on ordinal consistency, which is preferred to cardinal consistency, as suggested in the process of AHP (Kuenz Murphy 1993; Stein & Mizzi 2007). A main significance of this research is extending the original method of Chiclana et al. (2008) to enhance its effectiveness with: a scenario testing process to obtain an optimal number of necessary changes, and an automatic consistency checking process.

The consistency checking process only needs to be done in the first round of the Delphi-AHP method. The reason is clarified by Chiclana et al. (2008): when all the individual judgments meet a particular consistency threshold, then any weighted average of collective judgments will also meet that consistency threshold. Given the consensus process leans towards making the individual judgments closer to the collective ones, the individual consistency will be closer to the collective one. Therefore, it is not necessary to check the consistency of each expert in subsequent consensus rounds.

The consistency checking process of this study was carried out in three steps: 1) computation of consistency, 2) consistency threshold, and 3) consistency advice process. These three steps exactly followed the formulae in Chiclana et al. (2008), which are presented in Appendix 7. All algorithms of consistency-checking and consensus-building have been coded in MATLAB, which ensures quick and accurate computations. The validity of the coded procedures and algorithms was tested by using the same data presented in Chiclana et al. (2008) and achieving the same outcome. In the following sections, automatic consistency checking and consensus building, that are the main contributions of this study, are explained and results are presented.

6.3.4 *Automatic consistency checking and scenario analysis*

One of the dangers of using the Delphi method is that too many rounds may lead experts to lose interest and not return their questionnaires, a situation which would threaten the validity of the results. On the other hand, reaching the consistency threshold (β) is mandatory for all experts. Therefore, in this research, the inconsistent judgments are amended with advice values generated by the software implementing the three stages of the consistency advice system. This is a process that is iterative until the experts' responses for all matrices satisfy the consistency threshold.

The process of obtaining advice consistency suggests values to amend, so that the expert's consistency gets closer to the consistency threshold. However, the initial judgments should be kept as much as possible by making minimum changes necessary.

To ensure this, a percentage threshold δ= 35% is defined and each judgment matrix with more than δ of its values requiring update in the initial judgement values is omitted from further computations. An algorithm is developed, which identifies the optimal number (R) of necessary amendments. The algorithm first considers the least consistent value and automatically generates an advice value for it; then amends the original value to the new value and tests if the consistency is reached. It then considers the next least consistent value and repeats the amendment process until the consistency is reached. The algorithm in each amendment records the number of changed values and presents it in a percentage of the size of the matrix. The algorithm is coded into the software and suggests values of R for all inconsistent pairs of alternatives$(x_{i,}, x_j)$ related to expert *l* (cd_{ij}^l).

6.3.5 *Results of round 1*

The process of consistency checking was carried out based on the above discussions and detailed steps, as set out in in Appendix 7. Firstly values of cd_{ik} (consistency degree related to a pair of alternatives$(x_{i,}, x_k)$), cd_i (consistency degree associated to an alternative $x_{i,}$) and cd^l (consistency degree of the reciprocal judgment relation for expert *l*) are obtained and checked against consistency threshold $\beta = 0.9$. Then advice values are produced and recorded. Scenario analysis is performed to obtain the values of R^l and upon on them an automatic process of consistency checking is executed to obtain consistent cd^l. The detailed results of scenario analysis and consistency checking are outlined in Appendix 4.

Table 6-4 shows the summary of results of the application of the automated consistency-checking process. 2.1% of judgment matrices exceeded δ, which is small and thus indicated a good initial consistency for the majority of experts. The process updated an average of 10.2% of the initial expert judgments to achieve individual consistency for all experts. It is interesting to note that professionals demonstrated superior consistency as only one matrix was rejected, while four matrices from academics were found to be inconsistent and were omitted from calculations. The results also highlighted the most and least rational experts. While three experts (L9, L11 and L18) only presented one inconsistent matrix, L17 presented 8 inconsistent sets of judgment relations.

Table 6-4: Results of consistency checking process

Panel	Expert	Avg. $\boldsymbol{cd^l}$	No. of inconsistent matrices	Avg. $\boldsymbol{R^l}$	Avg. new $\boldsymbol{cd^l}$
Academic	L1	0.91	5	13.3%	0.94
	L2	0.93	2	1.0%	0.94
	L3	0.87	5	22.6%	0.92
	L4	0.88	4	11.4%	0.92
	L5	0.95	3	4.0%	0.95
	L6	0.90	5	11.0%	0.94
	L7	0.91	4	8.7%	0.93
	L8	0.89	5	18.0%	0.93
	L9	0.93	1	3.8%	0.94
	L10	0.91	5	10.9%	0.92
Professional	L11	0.92	1	5.0%	0.93
	L12	0.90	6	13.8%	0.93
	L13	0.90	4	17.8%	0.93
	L14	0.92	2	4.9%	0.92
	L15	0.92	3	2.9%	0.93
	L16	0.92	4	11.7%	0.94
	L17	0.89	8	20.6%	0.92
	L18	0.92	1	1.7%	0.93
	L19	0.91	2	7.7%	0.93
	L20	0.92	4	12.8%	0.94

6.4 Delphi-AHP round 2 (Consensus building)

The Delphi method is aimed at achieving consensus among all experts using multiple rounds, although a full consensus is not always possible, or necessary, in practice. In the integrated Delphi-AHP process, round 2 builds the required level of consensus through feedback matrices. Similar to the consistency-checking process, the method of Chiclana et al. (2008) is followed here. The process of consensus-building identifies experts whose initial judgment values are furthest from that of the whole panel, and then provides them with suggested changes in order to achieve the desired consensus. Figure 6-4 shows an illustration of this process; more detailed description is provided in Appendix 8.

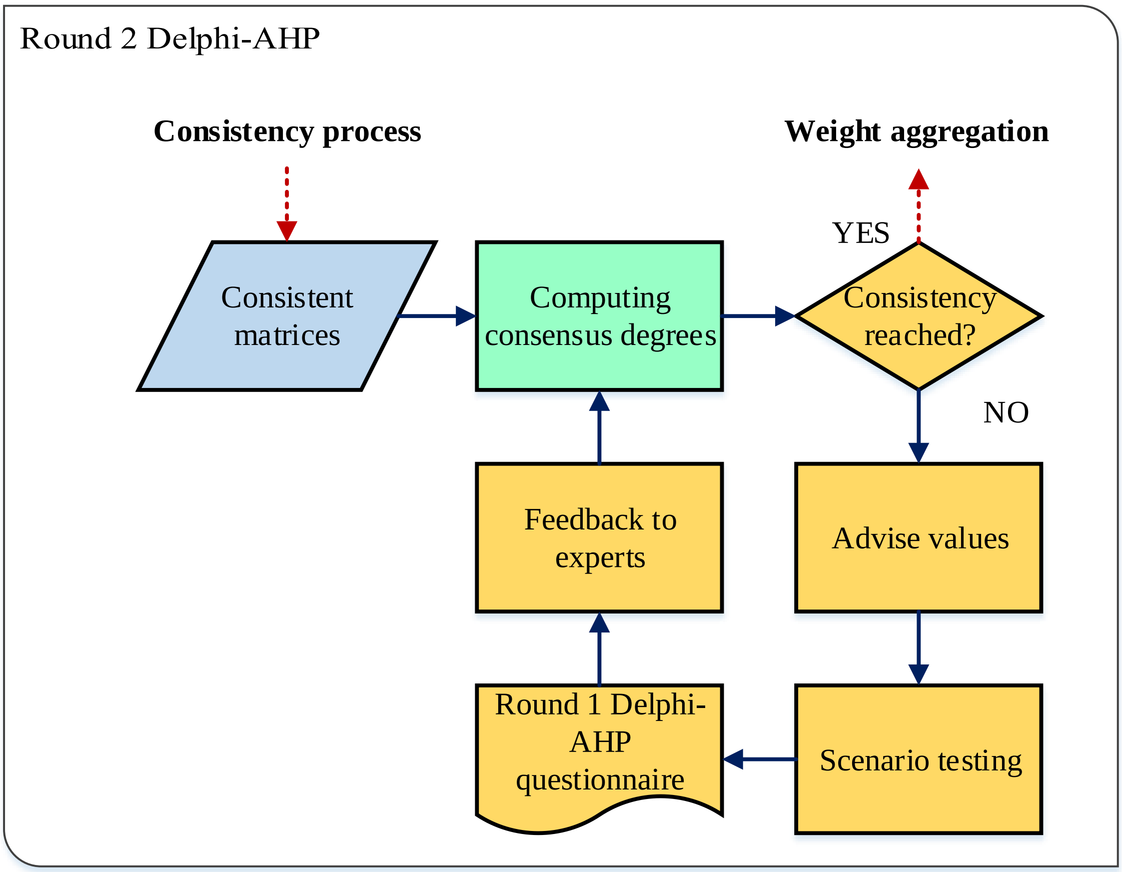


Figure 6-4: Round 2 Delphi- AHP process

6.4.1 *Feedback to experts*

To reach a desirable consensus, experts are provided with advised values towards their group's average opinion. The optimal number of advice values must be kept to a level which is not violating the initial judgments. Thus, similarly to the consistency-checking process, a threshold δ= 35% is defined as the maximum allowed final amendments of initial judgments. Second, at the same time, the amount of advices should be at a level that ensures the desired degree of consensus is obtained with a minimum number of iterations.

Given these two issues, a scenario analysis algorithm was developed to obtain the optimal number (R) of amendments. The algorithm first considers the furthest judgment value from the panel and automatically generates an advice value for it, then amends the original value to the new value and tests if the consensus is reached, otherwise it considers the next furthest value and repeats the amendment process until the consensus is reached. The algorithm in each amendment records the number of changed values and presents it in a percentage based on the size of the matrix. The algorithm is coded into the software and delivers values of R for all judgment relations of expert t (a_{ij}^t).

6.4.2 *Results of round 2 Consensus-building*

The consensus-building process above has been executed and the following results obtained. Firstly the values of ca_{ij} (consensus on pairs of alternatives (x_i, x_j)),ca_i (consensus on the alternative x_i), and cr (consensus of all alternatives) were obtained and tested against consensus ranges γ_1, γ_2 and γ_3 (Figure 6-5). Then, advice values were provided and the scenario analysis performed to obtain the optimal number of advice values for consensus (R). The results of scenario analysis showed three matrices, "Tasks", "Physical Resources", and "Tools and Methods" required higher percentage of changes than δ= 35%. However, it was predicted that not all of the advice values would be accepted by experts and that the accepted R would fall below δ. Therefore it was decided to proceed with these values at this stage.

The feedback questionnaires (Appendix 3) were sent to the experts. The questionnaire at this stage comprised of only those judgements from round 1 which were advised to be changed, together with the suggested new values. It requests that the experts reconsider their judgements with a choice to keep their initial opinion, modify to the panel opinion or change to a new value. All experts responded to round 2 questionnaires. Some of experts chose to keep their initial judgments and did not update them as suggested. Once all responses were received, the level of consensus based on the modified judgement values was re-evaluated. The detailed results of consensus-building and scenario analysis are presented in Appendix 5.

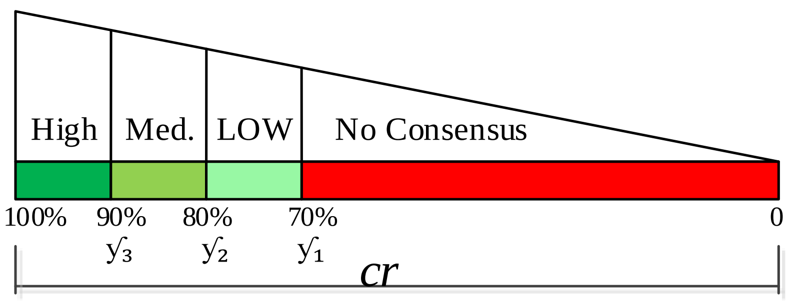


Figure 6-5: Defined ranges of acceptable consensus

Table 6-5 summarises results of round 2 of the Delphi-AHP process, which shows the initial consensus (initial *cr*), percentage of recommended change (R), percentage change made by the experts (accepted R), and final consensus (final cr) of all matrices. The result highlights that initially $average\ cr = 0.75$ is in the low consensus range. After one iteration, the average consensus improved to $cr = 0.81$, suggesting the success and effectiveness of the proposed Delphi-AHP GDM process. Nine matrices have medium level consensus, while the highest consensus is found for the "Information" category with 0.86. "Tasks", "Physical Resources", and "Tools and Methods" showed the lowest consensus levels with 0.79, 0.72 and 0.71 respectively, levels which fall into the low consensus range and are still acceptable in the context of this study. Also, as was expected, the values of accepted R for these three categories are below δ after review by experts.

Table 6-5: Results of consensus building

Matrix	Initial $\boldsymbol{cr}$	R	Accepted R	Final $\boldsymbol{cr}$
External	0.76	16%	13%	0.81
Internal	0.79	16%	10%	0.81
Capital Resources	0.73	30%	23%	0.81
Disciplines	0.72	18%	14%	0.84
People	0.82	15%	9%	0.84
Physical Resources	0.64	40%	33%	0.72
Information	0.83	8%	6%	0.86
Tasks	0.74	36%	21%	0.79
Time	0.75	29%	21%	0.81
Tools & Methods	0.62	45%	33%	0.71
Objectives	0.77	30%	25%	0.84
Technical	0.80	28%	21%	0.84
Average	0.75	26%	19%	0.81

6.5 Calculating final weights for PCIs

After the achievement of both consistency and consensus, the experts' final judgements are used to calculate the local weights of PCIs. This is done through a weight aggregation process. As discussed in Chapter 4, the geometric mean methods found to be superior to other methods and is thus selected. Given a_{ij} a judgment relation between indicator i and j $(i \neq j)$ in a $n \times n$ judgment matrix, the local weight of indicator i, w_i, is obtained through the following geometric mean formula:

$$w_i = \prod_{j=1}^{n} a_{ij}^{1/n} \quad (11$$

While local weights represent the relative importance of indicators within the given category, it is also useful to obtain the global weight of each indicator so that all indicators can be compared against one another, regardless of the category they belong to. One method to do this is to multiply the weight of the category with the local weight of the indicator. However, a main weakness of this method is that weights of indicators decline when the number of them in one category increases. Ramanathan (1997) proposed a solution to this problem by calculating the global weight gw_i of indicator *i* using its relative weight within the category. The formula is:

$$gw_i = \left(\frac{w_i}{w^*}\right) \times A \qquad (12$$

where w^* is the highest value in the category, A is the category's weight and w_i is the weight of indicator *i*.

A potential criticism of the formula above is that it assigns the same weight to the judgements of all experts, although the opinion of some experts could be considered of higher value than that of others. To address this concern, this research suggests three different scenarios that adopt different expert weighting strategies:

- *Scenario1. Non-weighted:* all experts (here ten academics and ten professionals) are considered equal and have the same weighting. This corresponds to the case above.

- *Scenario2. Practice weighted:* only the professional experts (here ten experts) are considered and academic experts are excluded. The selected ten professional experts are given the same weighting.

- *Scenario3. Competency weighted:* only those experts from both panels identified with "Advanced" and "Expert" levels of experience in megaprojects are selected. According to such criteria, eight professionals and five academics are included.

The local and global weights of each indicator and category in levels 2, 3 and 4 of the taxonomy calculated using the GM method for the above three scenarios are presented in Table 6-6 and Table *6-7*.

The values of the weights for the different scenarios disclose levels of agreement or disagreement between those. It should be noted that, in the external category, values of weights for sub-categories are an aggregation of indicators' weights in each category. For instance, among the external indicators, "EEC3 - Market unpredictability and uncertainty" appears more critical to scenario 2 and 3 than scenario 1. In contrast, "ESO3 - Significance on public agenda" appears less critical in scenario 2 (practice) than in scenario 1 (non-weighted). Similar disagreements between practice, non-weighted and competency scenarios can be observed among internal indicators; for example for "IORPE1 - Availability of human resources", "IPCTE6 - Variety of system components" and "IPRIN4 - Level of processing and transferring information". Overall, within the external category "EEC1 - Changing economy" is considered as the most influential indicator from scenario 1, whereas "EEC3 - Market unpredictability and uncertainty" is the most important element for the practice and competency scenarios. Size is regarded as one of the most distinguishing attributes of megaprojects, and all three scenarios support "IORCA1 - Size of capital investment" as the most important in the internal category.

Table 6-6: Local and global weights of external complexity indicators in three scenarios

Level2	Scenario 1 category weight	Scenario 2 category weight	Scenario 3 category weight	Level3 PCIs	Scenario 1		Scenario 2		Scenario 3	
					w_i	gw_i	w_i	gw_i	w_i	gw_i
Economy	34.84%	37.70%	36.69%	EEC1	13.00%	20.50%	12.14%	15.87%	12.42%	16.94%
				EEC2	9.10%	14.35%	10.26%	13.41%	10.11%	13.79%
				EEC3	12.74%	20.10%	15.30%	20.00%	14.16%	19.32%
Environmental	22.52%	21.62%	21.80%	EEN1	14.50%	10.48%	11.91%	11.47%	13.09%	11.48%
				EEN2	8.02%	5.80%	9.71%	9.35%	8.71%	7.64%
Legal & regulations	11.63%	11.01%	11.25%	ELE1	11.63%	5.23%	11.01%	5.84%	11.25%	5.92%
Politics	12.52%	14.60%	13.83%	EPO1	12.52%	5.85%	14.60%	7.74%	13.83%	7.28%
Social	18.47%	15.07%	16.43%	ESO1	4.72%	4.52%	4.11%	4.45%	4.53%	4.86%
				ESO2	4.32%	4.14%	3.58%	3.88%	3.84%	4.12%
				ESO3	9.43%	9.03%	7.38%	7.99%	8.06%	8.65%

Table 6-7: Local and global weights of internal complexity indicators in three scenarios

Level2	Level3	Scenario 1 category weight	Scenario 2 category weight	Scenario 3 category weight	Level4 PCIs	Scenario 1		Scenario 2		Scenario 3	
						$\boldsymbol{w_i}$	$\boldsymbol{gw_i}$	$\boldsymbol{w_i}$	$\boldsymbol{gw_i}$	$\boldsymbol{w_i}$	$\boldsymbol{gw_i}$
Organisation / Team of Delivery	Capital resources	15.78%	16.13%	16.02%	IORCA1	67.02%	5.43%	71.26%	5.86%	70.37%	5.63%
					IORCA2	32.98%	2.67%	28.74%	2.36%	29.63%	2.37%
	Disciplines	7.29%	7.08%	7.21%	IORDI1	33.54%	2.51%	37.87%	2.57%	36.01%	2.54%
					IORDI2	24.08%	1.80%	19.18%	1.30%	18.48%	1.30%
					IORDI3	22.62%	1.69%	23.03%	1.57%	24.78%	1.74%
					IORDI4	19.76%	1.48%	19.92%	1.35%	20.73%	1.46%
	People	12.73%	13.61%	13.30%	IORPE1	16.33%	3.14%	22.35%	4.79%	21.58%	4.42%
					IORPE2	22.80%	4.38%	17.21%	3.69%	17.11%	3.51%
					IORPE3	9.77%	1.88%	6.45%	1.38%	7.09%	1.45%
					IORPE4	15.06%	2.89%	12.51%	2.68%	13.71%	2.81%
					IORPE5	21.73%	4.17%	23.09%	4.95%	22.82%	4.68%
					IORPE6	14.32%	2.75%	18.39%	3.94%	17.69%	3.63%
	Physical resources	7.09%	8.82%	7.84%	IORPH1	40.07%	2.44%	41.12%	3.21%	41.57%	2.76%
					IORPH2	29.34%	1.79%	33.61%	2.62%	31.22%	2.07%

					IORPH3	30.59%	1.86%	25.27%	1.97%	27.21%	1.80%
Process of Delivery	Information	12.71%	13.29%	12.73%	IPRIN1	36.12%	3.97%	42.30%	4.83%	41.76%	4.48%
					IPRIN2	39.73%	4.37%	38.73%	4.42%	40.60%	4.35%
					IPRIN3	11.55%	1.27%	8.53%	0.97%	9.04%	0.97%
					IPRIN4	12.60%	1.39%	10.44%	1.19%	8.60%	1.03%
	Tasks	7.68%	6.93%	7.38%	IPRTA1	18.97%	2.30%	18.61%	2.02%	19.64%	2.31%
					IPRTA2	15.90%	1.93%	14.67%	1.59%	13.25%	1.56%
					IPRTA3	21.78%	2.64%	20.28%	2.20%	22.32%	2.62%
					IPRTA4	11.54%	1.40%	12.79%	1.39%	11.07%	1.30%
					IPRTA5	20.33%	2.47%	23.24%	2.52%	22.09%	2.60%
					IPRTA6	11.48%	1.39%	10.41%	1.13%	11.63%	1.37%
	Time	9.88%	9.47%	9.64%	IPRTI1	36.85%	3.40%	39.14%	3.44%	37.57%	3.39%
					IPRTI2	27.69%	2.56%	26.57%	2.34%	27.62%	2.49%
					IPRTI3	35.47%	3.27%	34.29%	3.02%	34.81%	3.14%
	Tools & methods	5.40%	4.58%	5.11%	IPRTO1	64.46%	1.86%	74.38%	1.66%	71.24%	1.80%
					IPRTO2	35.54%	1.02%	25.62%	0.57%	29.76%	0.75%
Characteristics	Objectives	13.83%	12.39%	13.09%	IPCOB1	11.99%	1.38%	12.26%	1.31%	12.06%	1.34%
					IPCOB2	14.51%	1.66%	11.29%	1.20%	12.82%	1.43%
					IPCOB3	41.47%	4.76%	42.30%	4.50%	41.34%	4.60%

					IPCOB4	32.03%	3.67%	34.15%	3.64%	33.78%	3.76%
	Technical	7.61%	7.70%	7.68%	IPCTE1	19.12%	2.37%	23.69%	2.80%	19.98%	2.53%
					IPCTE2	21.09%	2.62%	22.21%	2.62%	21.37%	2.70%
					IPCTE3	9.92%	1.23%	12.58%	1.49%	11.74%	1.48%
					IPCTE4	17.45%	2.17%	14.47%	1.71%	15.61%	1.97%
					IPCTE5	11.17%	1.39%	12.05%	1.42%	11.95%	1.51%
					IPCTE6	10.35%	1.29%	6.27%	0.74%	9.34%	1.18%
					IPCTE7	10.90%	1.35%	8.73%	1.03%	10.01%	1.27%

Figure 6-6 compares the three scenarios for the external category. Scenario 1 contains all experts so is placed in the base value, and then distances of scenarios 2 and 3 highlight the closeness of each scenario to the base. The vertical axis represents the difference in percentage terms. For example, the competency scenario includes more professionals than academics; therefore, its results are expected to be closer to the practice scenario than the non-weighted one, as is confirmed by the results.

While each scenario reports different values of PCIs weights, the decision on choosing a proper scenario for the next stage of the weight computing_process entirely depends on the project's situation. The competency judgments could be the most desired scenario in a specific project; however, the resulting weights are obtained from smaller number of experts which may be considered less reliable than scenarios with higher numbers of experts. In the rest of this thesis, only scenario 1 (non-weighted) is considered.

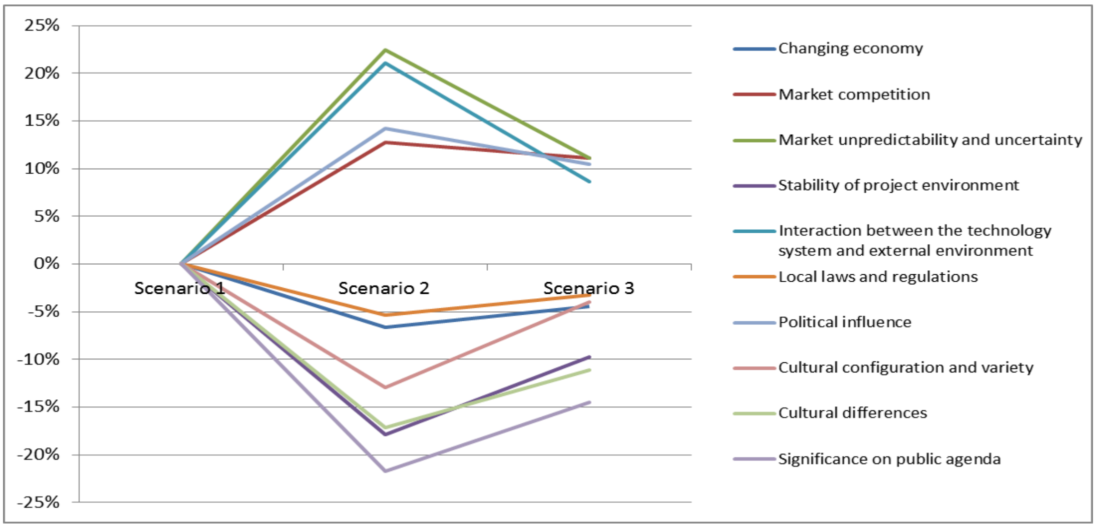


Figure 6-6: Variation of external PCIs local weights among 3 scenarios

6.6 Chapter summary

This chapter outlined the stages to obtain the ranking and weights of all PCIs when assessing project complexity. This was achieved by applying an integrated Delphi-AHP group decision-making method, explained in Chapter 4. It involved contributions from 20 experts with extensive experience and knowledge of megaprojects in the energy sector. Two rounds of questionnaires were used to achieve the required level of consistency for individual judgement and consensus for the group deliberations. Weights for all PCIs were calculated on the basis of the final opinions of all experts. Three different scenarios are presented to show the impact on these weights, if different experts are given different weights depending on their professions and levels of knowledge. The taxonomy of PCIs is applicable to all megaprojects. However, the weights for PCIs are only applicable to energy megaprojects, because they are established based on knowledge and expertise specific to this particular type of project. To compute the complexity of project, numerical scoring criteria for these PCIs also need to be defined, which is the subject of the next Chapter.

Chapter 7 Specifying Numerical Scoring Criteria for Project Complexity Indicators

7.1 Introduction

This chapter's focus is on establishing numerical scoring criteria (NSCs) for all PCIs. Establishing scoring criteria is an essential step in the development of a project complexity assessment method. However, it is often neglected in the existing studies of, and methods for, project complexity evaluation. To specify NSCs, this study follows a process, as summarised in Figure 7-1. A synthetic review of source literature was performed to extract relevant criteria that match the identified PCIs exactly. An interpretive analysis is then used to define those NSCs for which an exact match cannot be found. Finally, all extracted criteria are gathered and scoring metrics defined. To ensure the validity of the defined criteria, an expert review is performed using questionnaire survey; feedback from experts is used to refine the NSCs. Details are explained in the following sections.

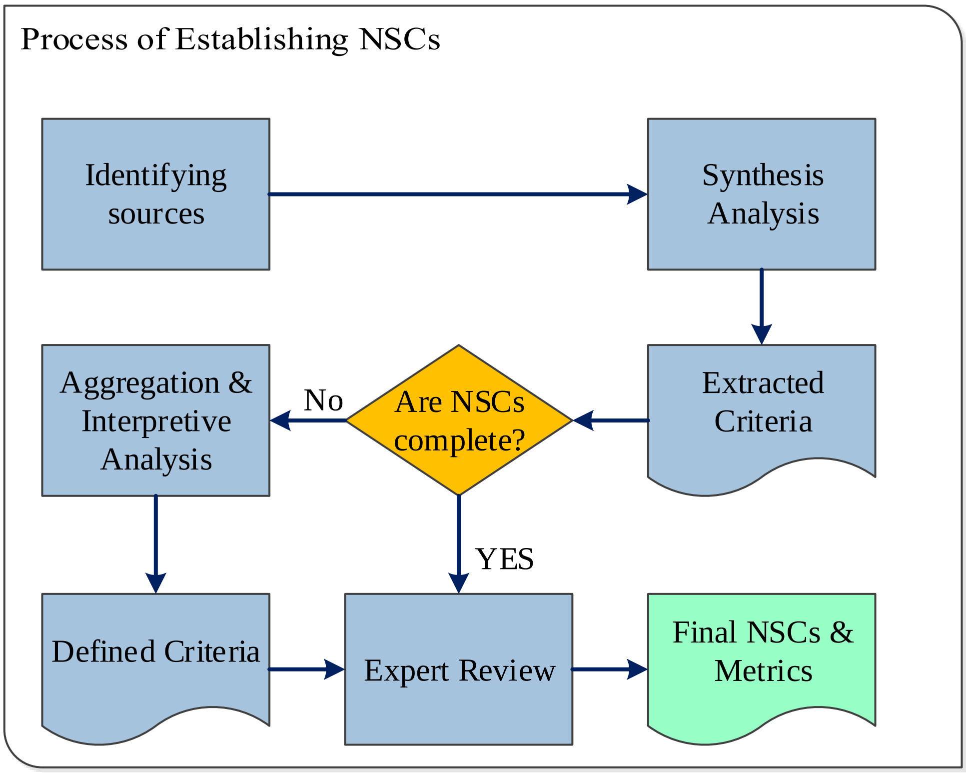


Figure 7-1: Process of establishing NSCs and metrics for PCIs

7.2 Extracting criteria from the literature

7.2.1 *Identifying sources*

Chapter 5 reports a systematic review conducted to identify the sources for eliciting the PCIs. It identified 50 literature sources, including academic publications, books, policy and reports. Given scoring criteria for PCIs is a particular aspect of PCIs, the same 50 sources are used for the search.

7.2.2 *Synthesis analysis*

The 50 literature sources were synthetically reviewed and analysed to extract criteria for all PCIs. The criteria and associated PCIs were then collated in a spreadsheet and repeating items removed. Then, the extracted criteria are synthesised to establish explicit NSCs.

As an example of a synthetic review, Locatelli & Littau (2013) identified performance variables of energy megaprojects, based on an analysis of eleven European case studies. They identified the "local residents are involved in the project" as one criterion, as local residents often come out against energy megaprojects, which increase the complexity of stakeholders' communications. Brooks (2013) extracted thematic influencing criteria from the analysis of a European megaprojects portfolio, such as "Green Peace or other international environmental activists have been involved in the project" or "the project has national public acceptability (no protest at national level)". She further concluded that the lack of these conditions leads to an increase of project complexity and consequently hinders the successful management of a project. It is proposed in this study to aggregate these points into a set of objective criteria for the "Significance on public agenda" PCI (Table 7-1). Similar synthesis analysis is done for 33 PCIs, for which explicit and comprehensive criteria can be identified. These 33 PCIs are highlighted in Table 7-4, Table 7-5, Table 7-6 and Table 7-7 with the "Process" column marked with "SA". An interpretive analysis is deemed necessary for the remaining 18 PCIs.

Table 7-1: Criteria for "Significance on public agenda" obtained from synthesis

Significance on public agenda	a. Green Peace or other international environmental activists have been involved in the project
	b. The project has national public acceptance (no protest at national level)
	c. The project has local public acceptance (no protest at local levels)
	d. Previous national/local similar project was successful
	e. Local residents are involved in the project

7.2.3 *Interpretive analysis*

The 18 PCIs remaining from the previous stage are categorised into three clusters based on their denotations:

- *PCIs which denote an extent or size attribute of project complexity.* This cluster includes four indicators: "Extent of capital investment", "Variety of resources", "Number of activities" and "Duration of project". For such indicators, it is problematic to determine absolute numerical thresholds for different levels of complexity, based on the number of activities or size of capital investment, due to inaccessibility of reliable data. Also, the absolute value may well vary for different companies based on their experience and capabilities: a project may be extremely complex in terms of activities for company A, but relatively simple and straightforward for company B. To tackle this problem and establish reliable numerical criteria, this research borrowed the concept of a "*competitiveness"* criterion, initially defined by Merrow (2011) to reflect relative cost overrun and schedule slip of megaprojects, compared to similar projects in the company. For instance, applying this relative complexity definition, the criterion defined for the "Number of activities" indicator is established as "What is the number of tasks in the project relative to other projects of organisations with similar scope?" Similar criteria are developed for the other three PCIs in this cluster.

- *PCIs which denote on dependency or interdependency*. This cluster includes six indicators: "Interdependence of objectives", "Dependencies between schedules", "Dependencies between tasks", "Process interdependencies", "Interdependence of information systems" and "Variety of institutional dependencies". Hass

(2007) argued that dependencies between solution components increase the complexity of large projects, therefore they should be limited or managed adequately. Also, as discussed in Chapter 3, Martin (2004) and Martin & Pierre-Alain (2004) mentioned dependencies as a critical element of internal complexity in a system. To measure the resulting complexity, they referred to the "degree of dependency" between two correlated elements to recognise whether the dependency is symmetric or asymmetric. This scaling of dependencies is further adopted in the management of complex international projects and programmes by Koster (2009). They scaled the severity level of dependencies from low to high for three types of dependencies: "normal dependency", "symmetric dependencies" and "asymmetric dependencies". For instance, in the case of "Dependencies between tasks", symmetric dependencies mean when the uncertainty of one task only changes the "*probability*" of the outcome of another task; and the asymmetric dependencies mean the uncertainty of one task leads to certain consequences and changes in the other task e.g. the need to redesign it. Therefore this dependency scale is employed to rate dependency related PCIs.

- The third cluster includes the 8 PCIs, each requiring different solution; they are: "Availability of human resources", "Level of trust", "Dynamic and evolving team structure", "Resource and raw material interdependencies", "Availability of physical resources", "Reliability of information systems", "Diversity of activities elements" and "Interaction between the technology system and external environment". Pitt et al. (1995) highlighted measures of effectiveness and reliability of information systems in the project environment as *tangibles*, *responsiveness* and *assurance*. Merrow (2011) associated data unreliability and errors in the front-end loading (FEL) process with time driven schedules and unavailability of data protocols. These five measures are specified as criteria for the "Reliability of information platforms" PCI. The same process of interpretive analysis is carried out for all 8 PCIs. The criteria from interpretive analysis are identified with "IA" in process column of Table 7-4, Table 7-5, Table 7-6 and Table 7-7.

7.2.4 *Defining numerical scales*

A numerical scale must now be established for each criterion that gives a score on how well a given project meets the criteria. The 1-5 Likert scale (see "Scores" column in example shown in Table 7-2) is used here, where 1 indicates the least and 5 the highest complexity level. The scoring of each PCI is presented in a question format, and the scores 1, 3 and 5 are explained based on the associated criteria to guide the assessor. Table 7-2 shows the complete NSC for the "Number of activities" PCI.

Table 7-2: "Variety of goals and objectives" PCI and its numerical metrics

Indicator	Criteria	Scores
Variety of goals and objectives	To what level are goals and objectives of the project varied?	1: If 0-2 criteria are met 3: If 3-4 criteria are met 5: If 5-6 criteria are met
	a. There is at least one major private stakeholder	
	b. Government owns at least 50% of project's share	
	c. Environmental activists have opinions and voice about the project	
	d. Local authorities and communities have opinions and voice about the project	
	e. Project's owner and client are different	
	f. Project receives financial support from international sources	

7.3 Expert review for refining NSCs

An expert review is used to evaluate the defined NSCs. The experts are asked about their opinions, recommendations and comments on the adequacy and appropriateness of the developed NSCs. The process of an expert review includes three steps: selecting the experts, design of questionnaire, and analysis of results and refinement of criteria.

7.3.1 *Selecting experts.*

For selecting the subject matter experts, those identified by the KRNW process (explained in Chapter 6) are considered qualified; however, participants should not be part of the previous stages of the study (Bryman 2012). Therefore, the 20 experts who took part in the Delphi-AHP process for establishing the PCIs, and their relative weights, are excluded. The remaining 58 experts are contacted and asked whether they would agree to take part in this review. Nine experts agreed to participate and sent back the filled questionnaires that were included with the invitation letter/email (see Section 7.3.2). These included three academics and six professionals with a high level of familiarity and knowledge about megaproject context and energy sector. The background information of the experts is summarised in Table 7-3.

Table 7-3: Background information of participants in expert review of NSCs

1) Experience in energy sector					
Years	6-10	11-15	16-20	>20	
Academia	0	2	1	0	
Professional	0	1	3	3	
2) Sub-Sector of professionals					
Sector	Oil&Gas	Renewable	Utility	Consultancy	Construction
Professional	2	2	1	1	0
3) Level of experience in megaprojects					
Level	Familiar	Knowledgeable	Advanced	Expert	
Academia	0	1	1	1	
Professional	0	0	3	3	

7.3.2 *Design of the questionnaire*

The questionnaire is designed in a spreadsheet format and experts can review the NSCs from a user's perspective. Appendix 6 shows the scoring criteria sheet for internal PCIs from the questionnaire. In each sheet, relevant PCIs and associated criteria and metrics are provided. For each NSC, experts are asked whether they agree with the definition of the criteria. If they do not agree, they are requested to provide their suggestions.

7.3.3 *Analysis of results, refinement of final NSCs*

The nine sets of assessments were then analysed for refining the criteria. In general, experts expressed agreement for the large majority of the NSCs. The following suggestions were received, which were taken into account to refine the relevant NSCs:

- EXT

1. “Market competition”: two experts commented that third criterion “None of the operators/modes (competitors) leaving the market” is actually repeating the meaning of first two criteria. The criterion is reviewed and redefined by focusing only on operation phase as “None of the operators/modes (competitors) leaving the market (or extremely reduce their operation) during the operation phase”.

2. “Local laws and regulations”: one expert suggested that he is not certain about the credibility of “The project is considered in the long term plan of the country's government” criterion; however none of other experts declared similar opinion, therefore no action was taken.

3. “Cultural differences”: initially two criteria were defined, “The project is mono cultural” and “There is an identifiable project culture”. The majority of experts (five experts) suggested that more criteria are needed. As a result, the source (Brooks 2013) is reviewed again and it is concluded to specify the mono cultural nature of a project into two distinct cultures: business and national-geographical.

- INT-Organisation

1. “Contract types”: initially two criteria “Contracts are subject to trade agreements” and “The results of the contract are dependent on the results of another contract” were presented. Two experts argued that more criteria were needed. As a result, the source (Treasury board of Canada secretariat 2009) was reviewed, but no additional sub-criterion could be identified. The search was thus extended to all sources and a new related criterion was extracted from Mancini (2013): “The organisation obtaining the contract will subcontract to other companies”.

2. “Support from permanent organisations”: Five experts declared their disagreement with “Project Manager has a position in the company’s board” criterion. The criterion was thus removed.

- INT-Process

1. “Interdependence of information systems”: four experts suggested that the question is not clear, therefore it was re-written in a more explicit way.

2. “Level of processing and transferring information”: three experts criticised the lack of clarity of the question, hence it was rewritten and expanded.

3. “Intensity of project schedule”: Two of the experts suggested that more criteria maybe available for this PCI. One of the experts suggested a related source (Thomas & Mengel 2008) on this matter. Review of the source led to the selection of a new criterion: “Tough physical or environmental conditions”.

4. “Applicability of project management methods and tools”: one expert declared he is unsure about the “Existence of sensitivity analysis” and “Appointment of a dedicated project manager in the team”. However because the rest of experts agreed on all criteria, no change was performed.

- INT-Characteristics

1. “Variety of goals and objectives”: two experts stated they were not sure about the importance of “Environmental activist have opinion and voice about the project” in a general context and it may only be applicable in specific cases. Since the argument from experts relied on only the importance of the criterion, and this research has tried to maintain comprehensiveness, it was decided to keep the criterion.

Table 7-4, Table 7-5, Table 7-6 and Table 7-7 provide the full list of PCIs and their associated NSCs, the process (synthetic/interpretive) through which criteria are obtained as well as sources.

The assessment of project complexity requires the user to score all PCIs, using the defined NSCs. Then, a complexity index (CI) can be computed for internal and external factors using the formula:

$$CI = \sum_{i=1}^{m} gw_i \times s_i \quad (13$$

Where gw_i is the global weight of indicator i ($\forall\ i\ \in \{ 1, \ldots, m\}$), m is the total number of indicators and s_i is the awarded score to the indicator. The CI value should be between 1 and 5, with the minimum total complexity value of a project is 1 and the maximum value is 5. The complexity levels of each sub-category of the taxonomy can also be calculated using this method.

This completes the process of development of the PCA method. The next Chapter presents the practical application of the developed PCA method in a case study.

Table 7-4: NSCs for PCIs - External category

PCI	Criteria	Score	Process	Scope	Source
Changing economy	To what extent are changes in the economy expected, based on following criteria: a. There is a stable economic environment during the project implementation phase b. No or few changes in the economic impact (Domestic) during the operational phase (Inflation rate, GDP) c. No or few changes in the economic impact (International) during the operational phase (Recession) d: No or few changes in energy prices	1: If all criteria are met. 3: If three or two criteria are met 5: If no or one criteria is met	SA	M	(Dimitriou et al. 2012; Brooks 2013; Mancini 2013)
Market competition	What is the level of market competition between competitor companies based on the following criteria: a. New operators/modes (competitors) entering in the market during the implementation phase b. New operators/modes (competitors) entering in the market during the operation phase c. No operators/modes (competitors) leaving the market (or extremely reducing their operation) during the operation phase	1: If no criteria are met 3: If one or two criteria are met 5: If three criteria are met	SA	M	(Brooks 2013; Mancini 2013; Locatelli & Littau 2013)

Market unpredictability	To what extent are market conditions, in terms of demand and supply, unpredictable?	1: Less than 20% 3: Between 20% and 40% 5: More than 40%	SA	M	(Merrow 2011; Brooks 2013)
Stability of project environment	To what extent are projects' external environments stable, based on the following statements? a. There is high level of market unpredictability b. There is high level of market competition c. There is high level of economic change	1:If no criteria are met 3: If one or two criteria are met 5: If three criteria are met	SA	M	(Merrow 2011; Brooks 2013; Flyvbjerg 2014)
Interaction between the technology system and external environment	What level of interaction or dependency between technological requirements of project and external environment is required?	1: Less than 20% 3: Between 20% and 40% 5: More than 40%	IA	G-M	(Koster 2009; Merrow 2011)
Local laws and regulations	Regarding local laws and regulations from the external project environment, how many of the following criteria are met: a. Permits are seriously delaying or withholding similar projects in the same country which causes slippage in overall schedule b. The authority has given a fine to the main contractor or one of the internal stakeholders in a	1: If 0-2 criteria are met 3: If 3-4 criteria are met 5: If 5-7 criteria are met	SA	G-M	(Merrow 2011; Bosch-Rekveldt et al. 2011; Brooks 2013; IPMA 2013)

	similar project				
	c. Permit requirements change repeatedly during front-end loading				
	d. Non stable legal environment (without any major changes in the legislation during the process time)				
	e. Changes in legislation relative to tendering processes				
	f. Changes in legislation relative to environmental law				
	g. The project is considered in the long term plan of the country's government				
Political influence	Regarding political influence in the external project's environment, how many of the following criteria are (will be) met?	1: If 0-1 criteria is met 3: If 2-3 criteria are met 5: If 4-5 criteria are met	SA	G-M	(Flyvbjerg 2014; Treasury board of Canada secretariat 2009; Locatelli & Littau 2013)
	a. There are changes in the project's scope due to political actions				
	b. Political pressure related to the project's milestone deadlines				
	c. Negative political influences depending on the degree of external funding				
	d. Project does not receive support from central government				
	e. Project does not receive support from local government				
Cultural configuration	To what extent should cultural configuration be taken into account based on the following criteria:	1: If 0-1 criteria is met 3: If 2-4 criteria are	SA	G-M	(Mancini 2013; Brooks 2013;

	a. Industrial regional benefits b. Aboriginal peoples c. Green procurement d. Relocation of staff e. Loss of employment f. Managing designated heritage assets	met 5: If 5-6 criteria are met			Wood & Ashton 2010)
Cultural differences	To what extent should cultural differences be taken into account based on the following criteria: a. The project is mono cultural (business culture) b. The project is mono cultural (national-geographical) c. There is an identifiable project culture	1: If three criteria are met 3: If one or two criteria are met 5: If no criteria are met	SA	G-M	(Brockmann & Girmscheid 2007; Dimitriou et al. 2012; Flyvbjerg 2014; Brooks 2013)
Significance on public agenda	Regarding significance of project in public, how many of the following criteria are met: a. Green Peace or other international environmental activists have been involved in the project b. The project has national public acceptance (no protest at national level) c. The project has local public acceptance (no protest at local levels) d. Previous national/local similar project was successful e. Local residents are involved in the project	1: If four or five criteria are met 3: If two or three criteria are met 5: If no or one criteria is met	SA	M	(Littau 2013; Locatelli & Littau 2013; Mancini 2013; Flyvbjerg 2014)
SA: Synthetic Analysis IA: Interpretive Analysis M: Megaproject G: General					

Table 7-5: NSCs for PCIs – INT-Organisation

PCI	Criteria	Score	Process	Scope	Source
Size of capital investment	Relative to other project investments cost in your organisation, what is the level of the project in terms of size of capital investment?	1: In the bottom 25% 3: Between 25% and 50% 5: In top 50%	IA	M	(Merrow 2011)
Variety of investors and financial resources	To what extent do the financial resources of the project vary regarding the following criteria? a. Project fully funded by private b. Project funded less than 50% by government c. Project funded more than 50% by government	1: a 3: b 5: c	SA	M	(Littau 2013; Brooks 2013)
Contract types	How many of the following statements are fit to the project in terms of contract types? a. The organisation obtaining the contract will subcontract to other companies b. Contracts are subject to trade agreements c. The results of the contract are dependent on the results of another contract	1: If no or one criteria is met 3: If two criteria are met 5: If three criteria are met	SA	G-M	(Merrow 2011; Giezen 2012a; Treasury board of Canada secretariat 2009)
Variety of institutional dependencies	To what extent, institutional dependencies in the project are varied? a. There are pooled interdependencies (each project unit performs completely separate functions)	1.a 3:b 5:c	IA	G	(Thompson 1967; Martin 2004; Martin & Pierre-Alain

	b. There are sequential interdependencies (each project unit in the overall process produces an output necessary for the performance by the next unit)				2004; Koster 2009)
	c. There are reciprocal interdependencies (the output of one project unit becomes the input of another, with the addition of being cyclical)				
Support from permanent organisation	How extensive is the commitment of the organisation's senior executive management, stakeholders, partners, and project sponsors to the successful completion of this project? Consider the following criteria:	1: If three or four criteria are met 3: If one or two criteria are met 5: If none of the criteria is met	SA	G-M	(Project Management Institute 2014; Treasury board of Canada secretariat 2009; Brooks 2013)
	a. A senior project sponsor or management champion is engaged				
	b. Stakeholders and partners are willing to reallocate resources if necessary				
	c. Senior executive management oversight is in place				
	d. Commitment from all stakeholders is confirmed				
Team cooperation and communication	What is the predicted level of communication between team members considering the following criteria:	1: If 3-4 criteria are met 3: If 2 criteria are met 5: If 0-1 criteria is met	SA	G-M	(Treasury board of Canada secretariat 2009; Merrow 2011)
	a. The project team has previously worked together				
	b. A low rate of conflict is expected or was seen				
	c. Interface management has been applied				
	d. The team communication plan is set and performing				
Availability of human	At which level are human resources (HR) available for the project, based on the following criteria:	1:If 6-8 criteria are met	IA	G-M	(Huselid 1995; Merrow 2012;

resources	a. The resource management system is set and performing b. The imbalances which might be caused due to non-availability of human resources is measured and mitigated c. At least 80% of the HR pool will be available during project operation d. At least in 80% of the times HR are needed, they will be available e. The project schedule is not aggressive f. There are no or few competing projects which are using shared resources g. Quality of labour is satisfactory h. The cost of HR is estimated and finance will be available during the project operation	3:If 3-5 criteria are met 5:If 0-2 criteria are met			Major Projects Authority 2012)
Level of trust	To what extent can the level of trust between team members or between teams be explained, based on following statements: a. There is a high level of competencies available (Trust based on a perception that team members are competent, and so will not let the team down) b. There is a high level of commonality available (Trust based on background, values, approaches, interests and objectives held in common	1: If all or four criteria are met 3: If three or two criteria are met 5: If no or one criteria are met	IA	G	(Spector & Jones 2004; Bosch-Rekveldt et al. 2011; Brockmann & Girmscheid 2007)

	c. There is a high level of security available (Trust arising from the feeling that nobody has anything to fear from the other members of the group)				
	d. There is high level of availability of information (Trust based on the fact that other team members share information important to the team proactively and clearly)				
	e. There is a high level of integrity available (Trust based on the fact that other team members maintain promises, are team oriented and behave towards goals in accordance with a moral code)				
Diversity of participants	How diverse are the participants in the projects?	1: If no or one criteria are met 3: If two or three criteria are met 5: If all or four criteria are met	SA	M	(Locatelli & Littau 2013; Littau 2013)
	a. The project has at least one foreign EPC company				
	b. More than one major stakeholder is present				
	c. Government is involved in the project				
	d. The private sector is involved in the project				

Dynamic and evolving team structure	What is the level of evolution within teams?	1: Teams are evolving and mostly reach performing level 3: Teams have some degree of evolving and mostly reach norming level 5: Teams have difficulty in evolving and mostly stay in forming or storming level	IA	G	(Katzenbach & Smith 1992)
Experience and capabilities within teams	Considering the following criteria regarding experience and capabilities in the team: a. The project will use a proven approach b. This type of project has been done before in the organisation and the same resources are available c. All needed functions are on the team d. Roles and responsibilities are defined e. A documented schedule is available	1: If 4-5 criteria are met 3: If 2-3 criteria are met 5: If 0-1 criteria are met	SA	G-M	(Treasury board of Canada secretariat 2009; Merrow 2011; IPMA 2013)
Interest and perspectives among stakeholders	How stakeholders interests of the project can be explained: a. All stakeholders goals and interest are identified b. A formal stakeholder management is set and put in place	1: If all or four criteria are met 3: If three or two criteria are met 5: If no or one criteria	SA	M	(Brooks 2013; Locatelli & Littau 2013; Littau 2013; Mancini 2013;

	c. There is a low level of conflicting interests among stakeholders d. There is a cooperative relation between client and contractors e. Successful experience with managing stakeholders in similar projects exists in the organisation	are met			Flyvbjerg et al. 2003)
Resource and raw material interdependencies	Which of the following statements describes resource interdependency level in the project: a. All resource dependencies identified b. Resource users are aware of dependencies and communicated c. Less than 20% of resources are directly dependent on each other d. If conflicts come up between users, they could be effectively resolved e. Dependency of resources does not affect project delivery	1: If all or four criteria are met 3: If three or two criteria are met 5: If none or one criteria are met	SA	G-M	(Parolia et al. 2011; Merrow 2012)
Variety of resources	Relative to the average of projects in your organisation (variety of resources which used in previous similar projects), what is the level of variety of resources in the project?	1: Equal to average or less varied 3: Between 25% and 50% more varied than average 5: More than 50% varied	IA	M	(Merrow 2011)

Availability of physical resources	In which level are physical resources available for the project based on the following criteria: a. The resource management system is set and performing b. The imbalances which might be caused due to non-availability of physical resources are measured and mitigated c. More than 80% of resources will be available during project operation d. There are no or few competitor projects which are using shared resources e. The cost of resources is estimated and finance will be available during the project operation f. Local contents are fully or relatively open for project use	1: If 5-6 criteria are met 3: If 2-4 criteria are met 5: If 0-1 criteria are met	SA	M	(Merrow 2012; Merrow 2011; Locatelli & Littau 2013)
SA: Synthetic Analysis IA: Interpretive Analysis M: Megaproject G: General					

Table 7-6: NSCs for PCIs – INT-Process

PCI	Criteria	Score	Process	Scope	Source
Availability of information	To what extent is information available for the project or is most likely to be correct based on the following criteria: a. There is use of new technology in the project	1: If no criteria are met 3: If one criteria is met 5: If two or three	SA	G-M	(Treasury board of Canada secretariat 2009; Merrow 2011;

	b. The condition that the basic data are very expensive or hard to obtain c. Lack of experienced or uninvolved main sponsors	criteria are met			Nguyen et al. 2015)
Reliability of information platforms	Based on the following criteria, how reliable are the projects' information platforms? a. The components (Physical facilities, equipment, and personnel) of platforms are tangible b. Platforms have high levels of responsiveness (Willingness to help customers and provide prompt service) c. Platforms have high levels of assurance (Knowledge and courtesy of employees and their ability to inspire trust and confidence) d. The project does not involve time driven scheduling e. There are acceptable levels of communication between platforms (Information protocols are available)	1: If 4-5 criteria are met 3: If 2-3 criteria are met 5: If 0-1 criteria are met	SA	G-M	(Pitt et al. 1995; Merrow 2011; Xia & Lee 2005; He et al. 2015)
Interdependence of information systems	What is the level of dependencies among the information platforms based on the following criteria: a. There are normal dependencies between platforms without any or low levels of uncertainty b. There are symmetric dependencies between platforms: between two correlated platforms, the uncertainty of one platform can only affect the probability of the changes of another platform	1: a 3: b 5: c	IA	G	(Martin 2004; Martin & Pierre-Alain 2004; Koster 2009; Worren 2012)

	c. There are asymmetric dependencies between platforms: between two correlated platform the uncertainty of one platform leads to changes in performing another platform e.g. modified ways of obtaining of data				
Level of processing and transferring information	Is an appropriate information management process adapted to collect, distribute, and protect relevant and important project information, such as designs, project plans, baseline and registers?	1: Comprehensive information management practices are adapted or planned to support the project throughout its life cycle. 3: Standard information management practices are planned or adapted and resourced 5: Minimal or no information management practices are adapted or planned within the project	SA	G	(Treasury board of Canada secretariat 2009; Pitt et al. 1995)
Diversity of sites and locations	Do geographical considerations influence the manner in which the project is conducted? Considering the following criteria:	1: If no criteria are met 3: If one or two	SA	M	(Merrow 2011; Dimitriou et al. 2012)

	a. Project activities or team members are distributed across a wide geographical area b. Labour must be imported to the project location c. Project sponsor is new to area	criteria are met 5: If three criteria are met			
Process interdependencies	What is the level of dependencies among the project processes based on the following criteria: a. There are normal dependencies between processes without or with only low levels of uncertainty b. There are symmetric dependencies between processes: between two correlated processes, the uncertainty of one process can only change the probability of performing of another process c. There are asymmetric dependencies between tasks: between two correlated tasks, the uncertainty of one task leads to changes in performing another task e.g. redesign the latter task	1: a 3: b 5:c	IA	G	(Martin 2004; Martin & Pierre-Alain 2004; Koster 2009; Worren 2012)
Dependencies between tasks	What is the level of dependencies among the project tasks based on the following criteria: a. There are normal dependencies between tasks without or low level of uncertainty b. There are symmetric dependencies between tasks: between two correlated tasks, the uncertainty of one task can only change the probability of the outcome of another task	1: a 3: b 5: c	IA	G	(Martin 2004; Martin & Pierre-Alain 2004; Koster 2009; Worren 2012)

	c. There are asymmetric dependencies between tasks: between two correlated tasks, the uncertainty of one task leads to changes in performing another task e.g. redesign the latter task				
Number of activities	Relative to other projects in your organisation, what is the level of the project in terms of the amount of tasks, considering elements or deliverables in the work breakdown structure?	1: In bottom 25% 3: Between 25% and 50% 5: In top 50%	IA	M	(Merrow 2011)
Unpredictability of tasks	To what extent tasks cannot be fully defined until the completion of previous tasks? Or delivery of task is not predictable? (These are tasks that may be understood but cannot be documented in detail due to dependency on results from a previous task or any matter of uncertainties.)	1: Under 10 percent 3: Between 10 and 30 percent 5: More than 30 percent	SA	G-M	(Treasury board of Canada secretariat 2009; Flyvbjerg et al. 2003)
Diversity of activities elements	To what extent, sub-activities and sub-tasks of are diverse? a. High technological diversity b. High diversity in communication platform c. Existence of different conflict orientation	1: If no or one criteria is met 3: If two criteria are met 5: If three criteria are met	IA	G	(Koster 2009; Worren 2012)
Duration of project	Relative to the average of project delivery duration in your organisation, what is the level of the project in terms of the project schedule?	1: In bottom 25% 3: Between 25% and 50% 5: In top 50%	IA	M	(Merrow 2011)

Dependencies between schedules	What is the level of dependencies among the project schedules (e.g. if the project is a programme) based on the following criteria: a. There are normal dependencies between schedules without or with only low levels of uncertainty b. There are symmetric dependencies between schedules: between two correlated schedules, the uncertainty of one schedule can only change the probability of the finish date of another schedule c. There are asymmetric dependencies between schedules: between two correlated schedules, the uncertainty of one schedule leads to changes in delivering another schedule e.g. rescheduling the plan	1: a 3: b 5: c	IA	G	(Martin 2004; Martin & Pierre-Alain 2004; Koster 2009; Worren 2012)
Intensity of project schedule	What is the level of schedule intensity based on following statements: a. Total tasks float time is less than 10% of whole project delivery time b. Resources to re-plan the urgent activities are hardly in access c. The project is a national project d. Tough physical or environmental conditions e. There is uncertainty about project impacts	1: If no or one criteria are met 3: If two or three criteria are met 5: If four or All criteria are met	SA	G-M	(Brooks 2013; Project Management Institute 2014)
Applicability of project management	Are reliable and effective project management methods and tools applied in the project based on the following criteria:	1: If 6-8 criteria are met 3: If 3-5 criteria are	SA	M	(Brooks 2013; Flyvbjerg 2014; Major Projects

methods and tools	a. Valid cost-benefit analysis considered	met 5: If 0-2 criteria are met			Authority 2012)
	b. No evidence of a general "optimistic bias" in the project				
	c. Risk analysis related with schedules, costs and project results				
	d. Existence of sensitivity analysis				
	e. Appointment of a dedicated project manager in the team				
	f. The megaproject is decomposed in many sub-projects				
	g. There was an effective learning process from other projects and(or) tasks in the same project				
	h. High level of competency of the project management team				
Variety of project management methods and tools	What is the level of variety among project management methods and tools based on following criteria:	1: If no criteria are met 3: If one or two criteria are met 5: If three criteria are met	SA	M	(Brooks 2013; Locatelli & Littau 2013)
	a. Heavy usage of planning by milestones				
	b. Heavy usage of Formal project management tool and technique				
	c. Usage of different performance metrics				
SA: Synthetic Analysis IA: Interpretive Analysis M: Megaproject G: General					

Table 7-7: NSCs for PCIs – INT-Characteristics

PCI	Criteria	Score	Process	Scope	Source
Variety of goals and objectives	To what level are goals and objectives of the project varied? a. There is at least one major private stakeholder b. Government owns at least 50% of project's share c. Environmental activists have opinions and voice about the project d. Local authorities and communities have opinions and voice about the project e. Project's owner and client are different f. Project receives financial support from international sources	1: If 0-2 criteria are met 3: If 3-4 criteria are met 5: If 5-6 criteria are met	SA	M	(Brooks 2013; Locatelli & Littau 2013; Mancini 2013; Bosch-Rekveldt et al. 2011)
Interdependence of objectives	What is the level of dependencies among the project objectives based on the following criteria: a. There are normal dependencies between objectives without or with only low levels of uncertainty b. There are symmetric dependencies between objectives: between two correlated objectives, the uncertainty of one objective can only change the probability of the reaching to another objective	1: a 3: b 5: c	IA	G	(Martin 2004; Martin & Pierre-Alain 2004; Koster 2009; Worren 2012)

	c. There are asymmetric dependencies between objectives: between two correlated objectives, the uncertainty of one objective leads to changes in stages to achieve another objective e.g. considering change in objectives or scope				
Transparency of objectives	To what extent are the project's objectives and delivery requirements clear, completed, and communicated?	1: All objectives and requirements are clear, complete, and communicated and comparative advantage of project fully understood. 3: Up to 10% of total objectives and requirements are not complete or are undocumented 5: More than 10% of total objectives and requirements are not complete or are unclear	IA	G-M	(Treasury board of Canada secretariat 2009; Merrow 2011)

Scope changing	To what extent project scope is changing or divers from planned scope or organisation's mandate and desired strategic outcomes?	1: The project is fully aligned and it explicitly contributes to the strategic outcomes of the organisation or programme 3: There is good alignment with the strategic outcome and there is an indirect contribution to the strategic outcomes of the organisation or programme 5: There is a weak alignment with the strategic outcomes, or scope differs significantly from planned scope	SA	M	(Lessard et al. 2014; Merrow 2011; Flyvbjerg 2014)
Level of innovation	What is the expected level of innovation within the project: a. High level of technical innovation	1: If no or one criteria are met 3: If two or three	SA	M	(Brooks 2013; Littau 2013)

	b. Appearance of relevant new technologies during the project implementation (planning, design, and construction)	criteria are met 5: If four of five criteria are met			
	c. Appearance of relevant (for competitors) new technologies during the project implementation (planning, design, and construction)				
	d. Tendering process favouring innovation				
	e. Using untried technology or materials (not previously used)				
Technological experience and capabilities	To what extent, technological experience and capabilities within the project is required?	1. Required technologies and experiences are available through similar practiced projects 3. Project is FOAK (First Of A Kind) or unique 5. Project is FOAK or unique with the highest level of innovation	SA	M	(Merrow 2011; Locatelli & Littau 2013)

Repetitiveness of process	Which of the following statements describes what can be adopted in the project:	1.The project can be decomposed into many sub-projects which can learn from other similar projects 3.The project can be decomposed in some sub-projects and there is a level of learning from other similar projects 5. The project can neither be effectively decomposed in sub-projects nor would there be any learning from other similar projects	SA	G-M	(IPMA 2010; Locatelli & Littau 2013)
Specifications interdependencies	What is the level of interdependencies among the final product specifications based on the following criteria: a. There are normal interdependencies between objectives without or low level of uncertainty	1: a 3: b 5: c	IA	G	(Martin 2004; Martin & Pierre-Alain 2004; Koster 2009;

	b. There are symmetric interdependencies between specifications: between two correlated specifications, the uncertainty of producing one specification can only change the probability of the producing to another specification. c. There are asymmetric interdependencies between specifications (between two correlated specifications, the uncertainty of producing one specification leads to changes in producing another specification e.g. redesign or change in quality requirements)				Worren 2012)
Technological varieties	Regarding technological variety of the project, how many of the following criteria are met? a. The project requires a high level (greater than normal: average of experienced similar project) of technological availability. b. The project requires technological customisation beyond normal configuration c. The project requires a high level of technological performance quality d. The project requires a high level of technological reliability	1: If no or one criteria are met 3: If two criteria are met 4: If three or four criteria are met	SA	M	(Flyvbjerg 2014; Lessard et al. 2014)

Variety of system components	Once there is a final product or goal within the project, to what extent can the variety of its components be described?	1: The final product or goal is mono modular with independent modules 3: The final product or goal is multi modular with independent modules 5: The final product or goal is multi modular with dependent modules	SA	G-M	(Shafiei-Monfared & Jenab 2012b; Brooks 2013)
Changing technology	What is the level of changes in technology before or during the project operation?	1: Off the shelf or new integration only 3: Minor modifications 5: Major modifications or substantially new technology	SA	M	(Merrow 2011)
SA: Synthetic Analysis IA: Interpretive Analysis M: Megaproject G: General					

7.4 Chapter summary

The chapter presented the process followed to establish NSCs for all PCIs. It is achieved through a review and synthesis of 50 literature sources. For 33 PCIs, relevant scoring criteria were found in different sources; they are synthesised and aggregated to form the NSCs. For the remaining 18 PCIs, suitable criteria could not found directly from the sources. They have to be established based on interpretation of existing information. Once the NSCs are defined, a 1-5 Likert scale is used to determine numerical scales for scoring each PCI.

To ensure the validity of the developed NSCs and scoring thresholds, an expert review was carried out. Nine subject matter experts, comprising three academics and six professionals, provided feedback. Overall, a high level of support was received from the experts for the specified NSCs; their suggestions helped to refine the NSCs.

Once the final NSCs had been established, all components of the PCA method were in place so that the practical application of the developed PCA method could be tested. Information relating to this is presented in Chapter 8.

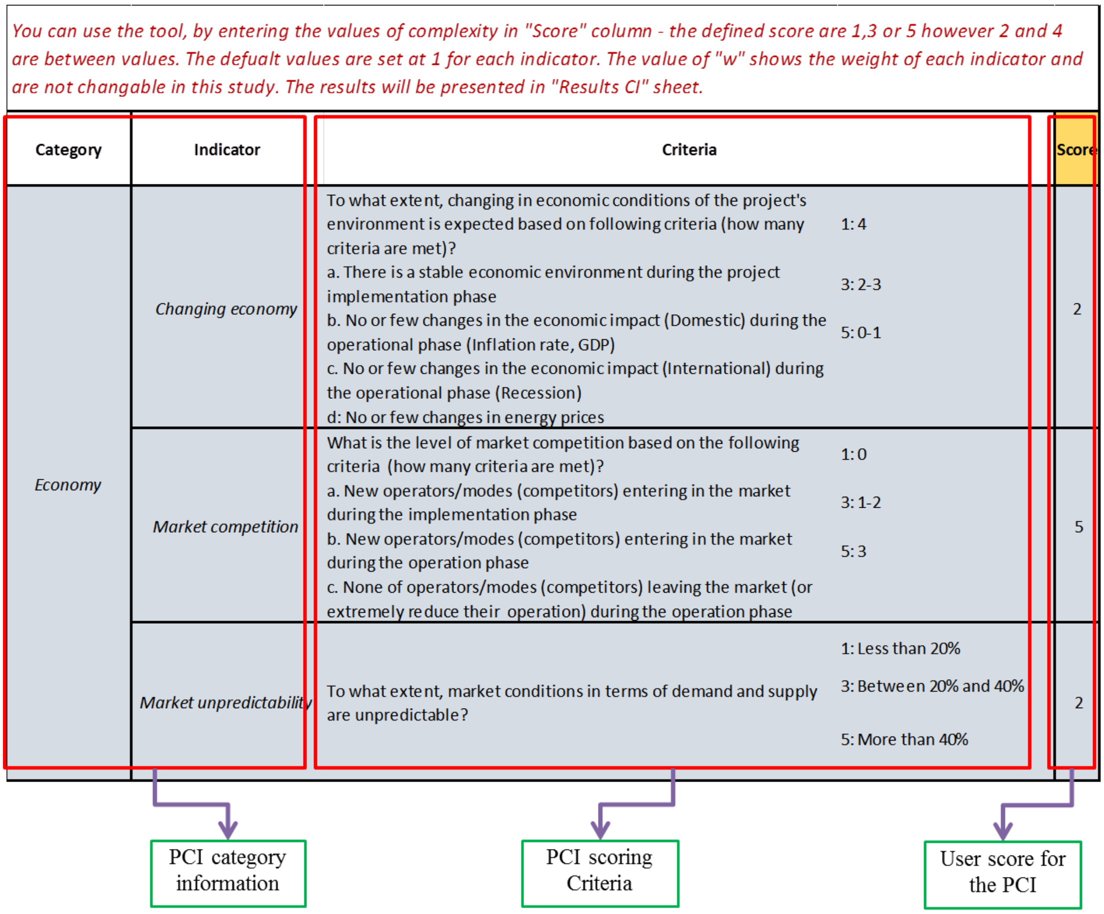
Chapter 8 Evaluation of the PCA method

8.1 Introduction

The developed PCA method needs to be evaluated to gauge its validity and applicability in practice. To achieve this, a case study is carried out using a real energy megaproject to demonstrate the application of the PCA method. This chapter describes the case study results, and is organised in two main sections. Section 8.2 describes the spreadsheet tool, which is implemented to facilitate calculations of the project complexity using the developed PCA method. Section 8.3 presents the results and analysis of applying the PCA tool in an energy megaproject case study. Finally, section 8.4 explains relation of project complexity in this research with theoretical complexity.

8.2 The PCA tool

The tool is developed in an MS EXCEL spreadsheet format and includes five main sheets: EXT (external indictors), INT-Organisation (internal organisation related indicators), INT-Process (internal process related indicators), INT-Characteristics (internal project characteristics related indicators), and results. Figure 8-1 shows a screenshot of the tool.



You can use the tool, by entering the values of complexity in "Score" column - the defined score are 1,3 or 5 however 2 and 4 are between values. The defualt values are set at 1 for each indicator. The value of "w" shows the weight of each indicator and are not changable in this study. The results will be presented in "Results CI" sheet.

Category	Indicator	Criteria		Score
Economy	*Changing economy*	To what extent, changing in economic conditions of the project's environment is expected based on following criteria (how many criteria are met)? a. There is a stable economic environment during the project implementation phase b. No or few changes in the economic impact (Domestic) during the operational phase (Inflation rate, GDP) c. No or few changes in the economic impact (International) during the operational phase (Recession) d: No or few changes in energy prices	1: 4 3: 2-3 5: 0-1	2
	Market competition	What is the level of market competition based on the following criteria (how many criteria are met)? a. New operators/modes (competitors) entering in the market during the implementation phase b. New operators/modes (competitors) entering in the market during the operation phase c. None of operators/modes (competitors) leaving the market (or extremely reduce their operation) during the operation phase	1: 0 3: 1-2 5: 3	5
	Market unpredictability	To what extent, market conditions in terms of demand and supply are unpredictable?	1: Less than 20% 3: Between 20% and 40% 5: More than 40%	2

Figure 8-1: Screenshot of user interface

The weights of all indicators (described in Chapter 6), are embedded in the tool. Once the user scores all the PCIs, a complexity index (*CI)* is calculated for internal and external categories, as well as at the sub-categories' level. The *CI* results are presented as spider diagrams to assist comparisons and understanding of the results; an example is shown in Figure 8-2. The tool is given to the case study project team to apply it in their project.

External

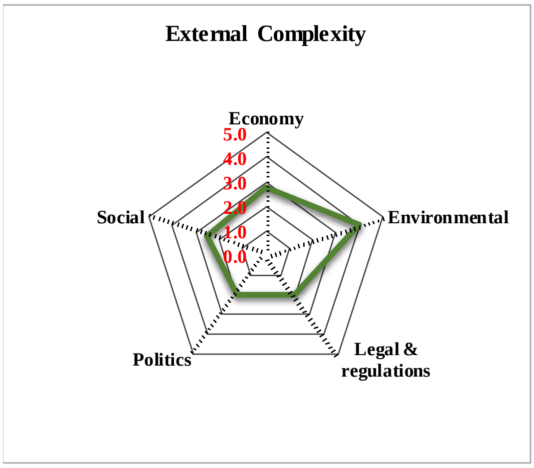
Category	CI
Economy	2.78
Environmental	4.00
Legal & regulatio	2.00
Politics	2.00
Social	2.53

CI(EXT)	2.86

Internal

Category	CI
Capital resources	4.00
Disciplines	2.68
People	2.54
Physical resources	3.49
Information	4.40
Tasks	2.96
Time	2.55
Tools & methods	3.64
Objectives	3.65
Technical	2.74

CI(INT)	3.17



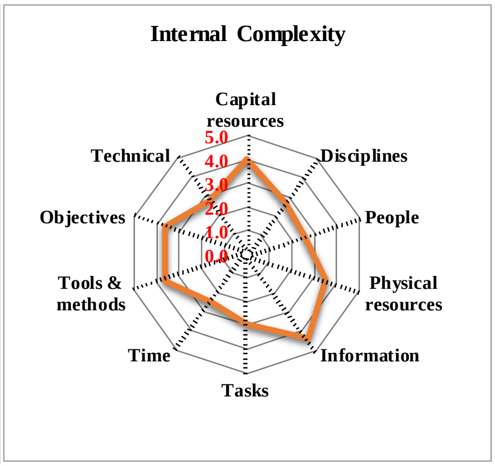


Figure 8-2: An example of results from the PCA tool outputs

8.3 The case study

The main aim of the case study was to test the application of the developed PCA method in practice. In addition, it will also explore problems that may exist with the developed PCA method; for instance, revealing confusing terminologies, difficulties in applying the method or understanding the results. The results of the case study will help to refine the PCA method. Specific objectives include:

- To test the function of the developed PCA method and tool by calculating the complexity of a real world project;
- To explore the levels of complexity in different aspects of complexity and determine the sources of complexity in the project;
- To obtain the feedback from practitioners in order to improve the PCA method and tool.

To achieve the above objectives, the case study is carried out following the process illustrated in Figure 8-3.

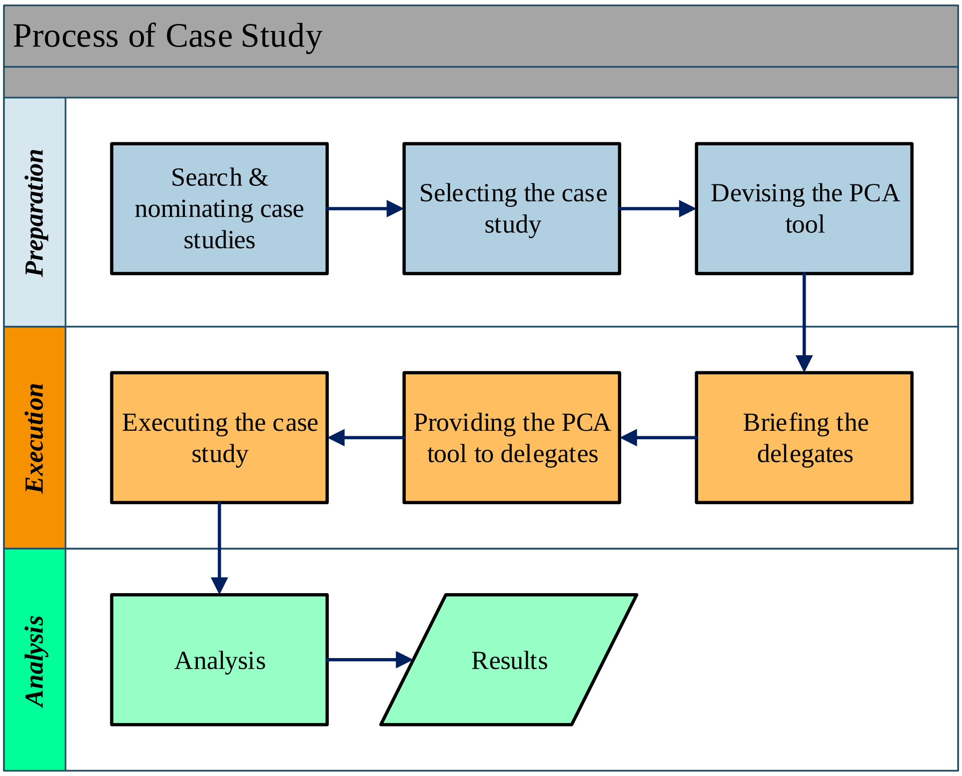


Figure 8-3: Process of case study in research

The process involves three main stages preparation, execution and analysis.

8.3.1 *Preparation*

This stage firstly identifies the nominated projects. The two main criteria used for selecting case studies are: they need to be energy megaprojects and they need to be accessible. Access to people and information, in order to carry out a case study, is essential. To do this needs support from top management, for allowing the sharing of project information. Seven energy megaprojects across the world were considered and their project teams contacted. Six companies refused to participate due to sensitivity of information and only one company confirmed willingness to cooperate on the condition of full anonymity and confidentiality. Therefore, that energy megaproject is selected for the case study. The information of the case study project is described below, in a way that no identifying information is revealed.

Background

The project is related to one of the world's largest reservoirs of natural gas condensates. Development of the field is planned in multiple phases; each phase has an average capital cost of more than US$1 billion, and will be executed by international oil & gas contractors working in partnership with local companies. This case study is conducted on the development of two phases, referred to as A and B, which are at the tendering stage. Both projects will begin at almost the same time and will progress in parallel but in different fields of the main reservoirs. Both are sponsored and managed by a national oil and gas company. The development programme has been delayed and interrupted due to different technical, contractual, financial and political issues. The development of the two phases is a typical example of energy megaprojects. Assessing project complexity for these two megaprojects can provide valuable information to help the project management team adopt appropriate complexity management strategies. In order to provide a reference, a set of completed phases was also analysed, including eight phases currently in operation (coded as OPT). Table 8-1 provides summary information about phases A, B and reference OPT.

Table 8-1: Information of case study projects

Phase /s	Contractor	Development start	Production start	Budget*	Products
A	Consortium of international and local	2016	2018	3.1	Natural gas / Condensates
B		2016	2019	3.6	Natural gas / LPG / Condensates / Sulphur
OPT		In operation		2.1**	/ Natural gas / LPG / Ethane / Condensates / Sulphur

*: US billion dollar **: Average spent budget of eight phases

8.3.2 *Execution*

At the start of this stage, the company chose one of its top directors to facilitate the execution of the case study. The researcher explained about this research and details of the case study through two briefing meetings (using Skype) with the facilitator. The PCA tool and a brief user manual were provided. During the meetings, it was agreed that the participants should include the project managers of the two energy megaprojects A and B, as well as a project director with extensive knowledge of the completed phases (OPT). Another two briefing meetings took place with all participants, to explain the process, their responsibilities and the use of the PCA tool. Table 8-2 shows background information of team members involved in the case study.

Table 8-2: Background information of case study execution team

Phase	Position	Years of experience	Sector	Experience Megaprojects
A	Project Manager	22	Offshore – Onshore / Oil & Gas	Advanced
B	Project Manager	18	Offshore – Onshore /Oil & Gas	Advanced
OPT	Project Director	27	Offshore – Onshore / Oil & Gas / Infrastructures / Government	Advanced

The assessment of project complexity of each phase and OPT started by scoring all PCIs. The project manager of each of phase A and B and the project director for OPT needed to award each PCI a score of 1-5 based on its NSC. After all the PCIs are scored, a complexity index (CI) is computed for internal and external factors using the formula defined in Chapter 7. The results are presented visually instantly, similar to that as shown in Figure 8-2.

8.3.3 *Analysis and results*

This stage includes two main steps: (1) the team considers the computed values of *CI and* proposed actions to mitigate the complexity; (2) the team provides feedback about the practical use of the PCA tool from the project team's perspective.

Developing strategies/actions to cope with project complexity

The computed values of *CI* for phase A and B are compared with that of OPT as a benchmark. The results initially were presented in spider diagrams; however, due to the request of the team (explained in the next section), a new graphical presentation is provided in the form of bar charts. Figure 8-4 depicts a computed final *CI* for each project. It also compares weighted aspects of project complexity within and among projects. Phase A shows a higher degree of complexity than OPT and phase B, in both internal and external categories ($\mathrm{CI(A)} > \mathrm{CI(OPT)} > \mathrm{CI(B)}$). In the internal category, the most complex aspect of phase A is 'objectives', followed by 'capital resources' and 'people'. Project B shows the highest complexity in 'capital resources', followed by 'physical resources' and 'objectives'. In the external category, the overall values of *CI* are reasonably close for all projects, but differ at sub-categories levels. While phase B is more complex than phase A and OPT in 'economy' and 'environment', it is much less complex in 'law and regulations', 'politics' and 'social' factors.

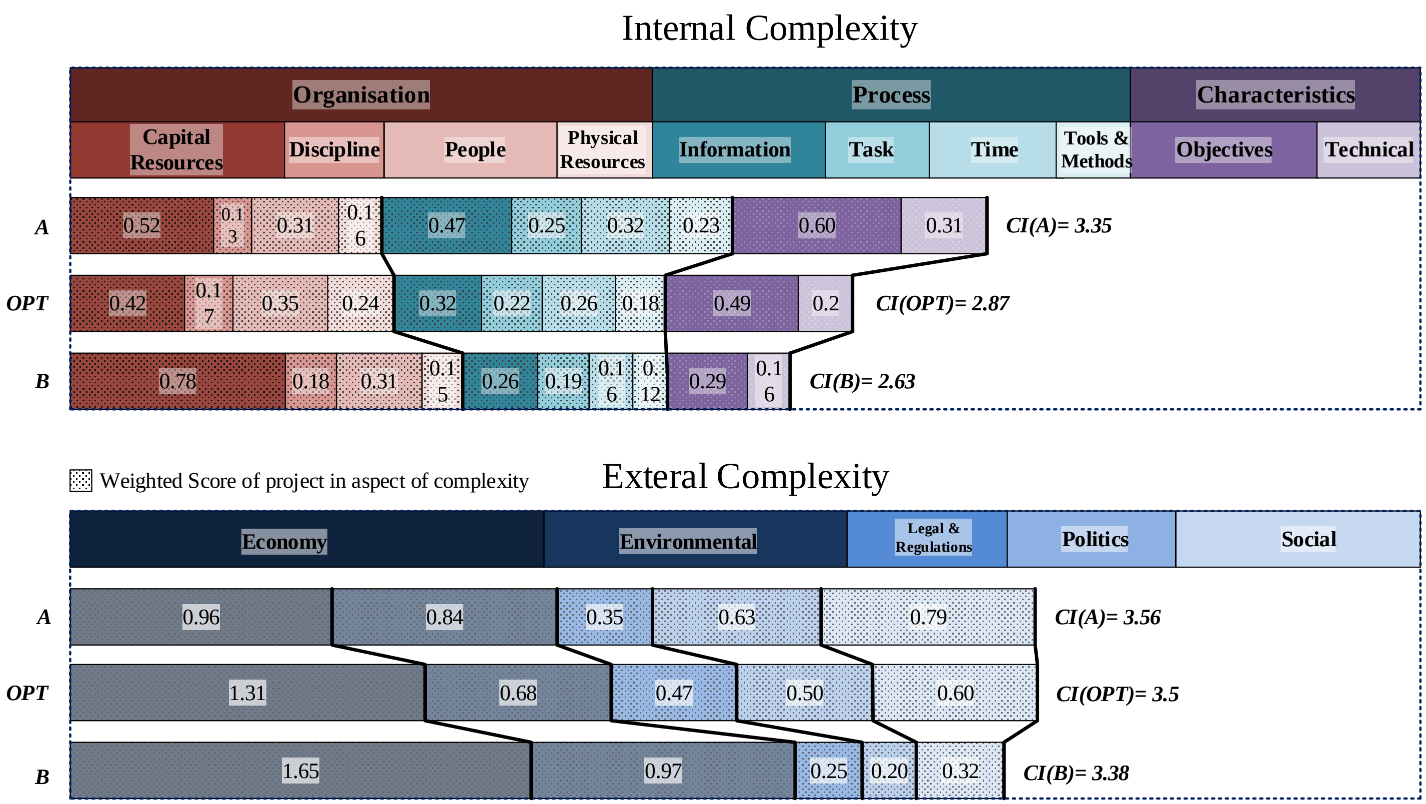


Figure 8-4: Level of complexity in aspects of internal and external complexity and values of CI

By reviewing the results of the complexity assessment, the project team was able to propose management strategies specific to each project. These proposed strategies and their rationale are summarised in Table 8-3.

Table 8-3: Strategies to cope with project complexity for the case study

Category / Aspect			Strategy/action
Internal	Organisation	Capital resources	Phase A and B are significantly more complex than OPT with regard to 'capital resources' complexity. It is also the most complex aspect in phase B. Therefore the project team suggested the need to establish a dedicated capital management system within the overall project management organisation to manage the financial resources during development of phases.
		Discipline	The complexity level of phase B is almost the same as that of OPT, while the project complexity of phase A is lower. The OPT phases did not experience any major difficulties in this aspect, therefore similar disciplines can be adopted for Phase A.
		People	Project complexity in OPT shows slightly higher degree of complexity than phases A and B, which are in the same level. It is noted that there were issues in this aspect when managing OPT phases, specifically in the availability of human resources, diversity of participants and experience within teams. Availability of human resources and diversity of participants are also scored 5 in phase A. Therefore, the team recommends these critical issues require the human resource department to be well involved before starting execution of new phases.
		Physical resources	In the execution of OPT phases, the company implemented a dedicated supply and maintenance system (DSMS) and mandated all contractors to adopt it. As a result, issues and failures had been managed effectively during the development of OPT phases. The team recommends the application of DSMS in phases A and B as well.

	Process	Information	The assessment of phase A raises concerns about the high level of complexity in availability and reliability of information. The *CI* of phase A is greater than that of OPT, therefore the team considered a review of initial evaluations and information of this phase. Phase B did not raise any concern (since its score is lower than OPT) and no specific remedy had been considered in this aspect.
		Tasks	Phase A is more complex than OPT, while phase B is less complex. The higher level of complexity of phase A is due to diversity of location. However, it was a similar issue in the development of OPT and the project team are experienced in dealing with this problem, therefore no specific strategy was recommended. The uncertainty of tasks is also associated to the application of new technologies in phase A. On that aspect, the team recommended delegation to a professional consultancy or a corresponding internal department. No specific action is suggested for phase B.
		Time	Intensity of the project schedule in phase A is critical due to the follow-up phases depending on the timely completion of this phase. Therefore complexity of this category for phase A is higher in OPT and B. However, the complexity was experienced in OPT, and the company knows how to handle it. Due to its significance, the team still decided to suggest a number of mitigating actions such as balanced contracting and safety budgets. Phase B was scored lower with no specific action suggested by the team.
		Tools & methods	Phase A is more complex due to the variety of project management tools and methods involved. The problem is caused by the hiring of new contractors for the development of this phase, who use different project management platforms. The issue is referred to the project management department to offer solutions. Phase B is less complex than OPT in this aspect and no specific action is required.

	Characteristics	Objectives	Objectives in phase A are the most significantly complex aspect in the internal category. The unreliability of initial estimations of the production capacity has led to only few contractors having shown interest in bidding. As a result, a main contractor has not been selected. This caused higher complexity in the variety and interdependence of objectives. Also there is a possibility of further changes which may cause excessive complexity in transparency of objectives or even scope changing issues. The project team invited a professional consultancy firm to review the initial production forecasts in order to attract more contractors to the project. However, this might increase costs and delay the completion date; hence, the issue should be raised with the programme board. Phase B entails less complexity in this aspect and requires no action.
		Technical	Similar to objectives, technical complexity of phase A is significantly higher than of OPT. This is due to the use of a particular location, new techniques, causing higher complexity in technological experience, technological variety and changes. The recommended action here is to consider whether experienced techniques can in fact be used instead in this phase with extra cost. Phase B requires routine technology, so its complexity level in this aspect is significantly lower than phase A and OPT, and no specific action is required for that phase.
External		Economy	Phase B is more sensitive to changing economy, market competition and market uncertainty because of its portfolio of products. Therefore, the degree of 'economy' complexity in phase B is greater than phase A. The production of the OPT phases has been significantly obstructed by economic fluctuation which mainly were out of control of project sponsors. As a result, the team advise to implement a long-term strategic plan with cooperation with the ministry of energy to predict and minimise the negative impacts.

	Environmental	A and B are more complex than OPT in the environment aspect. The project environment is considered unstable and this influences phase B more because of type of products in its portfolio. The experience of OPT in setting new types of contracts to tighten the sale will help with the management of high complexity of phase B. Phase A is also high due to increased complexity of interaction between technology and the external environment, resulting for the fact that the technology is new to the company. The team suggested to investigate the possibility of Transfer of Technology (TOT) for this phase.
	Legal & regulations	Phase A, due to its location has higher complexity than Phase B. OPT initial phases development was hindered by difficulties encountered with local rules and regulations because of lack of local delegation and communication system with local authorities. However, during the latter phases of OPT the project team successfully implemented such a system to manage complexity of this kind. Since phases A and B have a lower complexity in this regard, the same system should be effective for both phases.
	Political	Political complexity of phase A is far higher than phase B and OPT. Because of the political situation, international contractors have not showed interest in participating in phase A. On the other hand, this phase essentially needs technology that is not available to local contractors and needs to be supplied by international companies. To address this, it is decided that a separate team be put together during the project tendering and operational stages to manage political issues and communications with the government. Phase B has a much lower complexity in this aspect.

	Social	Gas field development in general is considered as a significant agenda in the eyes of the general public and media due to a number of issues such as national pride, delays and overspent budgets. In addition, cultural differences among the sponsors, main local contractors and international contractors have increased social complexity. This issue is more significant in phase A due to its dependability on external suppliers and the introduction of a new main contractor. During the execution of OPT phases, close communication with national media was established to increase public awareness of the project and their achievements. The same approach is followed in phase A and B.

The above recommendations by the case study team demonstrated an effective practical use of the PCA method and tool. However, comprehensive complexity management is beyond the scope of this research. How practitioners interpret the numerical values of project complexity in a real project situation, and take action based on the assessment, represent significant outcomes from the case study.

Feedback about the practical use of the PCA method

The case study team also provided feedback on the practical use of PCA method and tool. The team expressed their opinions and recommendations by addressing two open-ended questions:

- *"Please indicate your comment about indicators regarding their definitions or unclear terminology".*
- *"Please indicate your comment about practical use of the PCA tool".*

The responses from case study team are centred in two areas:

1. Team members expressed concerns regarding the ambiguity of some terms:
    - "Physical resources". What exactly do they include?
    - "Diversity of activities elements". What are those elements exactly?
    - "Variety of project management methods". Are they varied in number or in type or among different contractors?

Responding to these comments, the definitions of above indicators have been refined and made clearer. For example, a new explicit definition is provided for "Physical resources", now defined as: "Matters regarding machinery, infrastructures and goods which are imperative for project execution".

2. Regarding the use of the tool, the experts requested more graphical presentation of the results. Addressing this request, a customised bar chart (*Figure 8-4*) has been designed and added to the presentation of results. In general, the experts expressed a positive experience working with the tool and described it as "smooth", "applicable", "meaningful" and "capable".

A number of conclusions can be drawn from the case study:

- The PCA method/tool is easy to use as a tool for practitioners and project teams during their project planning and management process;
- It is able to help professionals to identify complexity issues, and to consider as well as develop mitigating measures in response to these issues;
- From the final *CI* value, the level of complexity can be easily cascaded to the lower levels. It enables the project team to take actions on desired levels of strategies, either detailed actions or more overall macro actions.
- The definition of PCIs and method of assessment is not limited to any specific stage of project. Therefore, it can be implemented to provide continuous evaluation and monitoring during the life-time of the execution of a project.
- Graphical as well as numerical results can be used to assist discussion within the project team and with outside experts in order to develop mitigating, complexity reducing strategies.

8.4 Reflection on the adopted research approach

Since all aspects of the developed PCA method and its practical application are introduced, it is time to reflect on the adopted research approach in addressing the project complexity problem. The literature review in Chapter 2 established that project complexity is due to the existence of magnitude of elements in a typical project and the interactions between these elements. Such a complexity is further complicated by the fact that these different project elements and the interactions between evolve throughout the life cycle of the project. Some researchers investigated project complexity by trying to understand the inner working mechanism of project elements and their interactions. These are reviewed in Chapter 3 under sections "3.2.1 process-base methods" and "3.2.2 numerical methods". These existing efforts failed to produce a common complexity network model or a simulation formula that can be used for all projects. In addition, their research outputs are difficult to be applied in practice because they tend to use terminologies to describe project complexity that are unfamiliar to project management practitioners.

In recent years, a growing number of researchers, such as Vidal et al. (2011), Owens et al. (2011), Xia & Chan (2012), and He et al. (2015), adopted a different approach to investigate project complexity. Instead of focusing on the essence of complexity, they tried to identify a list of factors related to a project that have an impact on its complexity. This approach may not lead to an accurate description of project complexity; but it will help identify the important factors that need to be considered when addressing the project complexity problem. Therefore, it can offer more practical help to project management professionals. Based on this rationale, the study also adopted this research approach. But, compared with existing studies using the same approach, this study has made some unique contributions toward addressing the particular problem of complexity in energy megaprojects.

8.5 Chapter summary

This chapter presents an energy megaproject case study undertaken to test the effectiveness of the PCA method. The case study involved an offshore gas field reservoir development programme. Two phases of A and B from development programme under tendering stage were selected. Both phases are typical energy megaprojects. A team from the company was asked to assess the project complexity of phases A and B as well as of eight completed phases (OPT) using the PCA tool. Afterwards, the team was asked to provide recommendations and feedback on the use of the PCA method and tool. The experience showed that the tool can be effectively applied in real world projects to assess project complexity and help develop necessary mitigating measures to reduce such complexity.

Chapter 9 Conclusions and Recommendations

9.1 Introduction

This chapter presents the main conclusions of this research. It begins with a reflection on how the aim and objectives, as set out in Chapter 1, have been achieved. It then goes on to discuss the study's contribution to knowledge, its limitations and the potential directions for future work.

9.2 Addressing research objectives

This research is aimed at developing a comprehensive, robust and practical method for project complexity assessment (PCA) of energy megaprojects. This aim is accomplished through five specific research objectives,

1. *To evaluate existing methods for assessment of project complexity and identify the perceived gaps between theory and practice*

A literature review on megaprojects (Chapter 2) recognised energy megaprojects as critical globally due to the world's increasing energy needs. However, their successful delivery is often hindered by several failures, such as cost overruns, schedule and production slips. Project complexity is found to be one of the main contributing factors to these failures. Chapter 2 also explored the context of project complexity and highlighted the lack of consensus on the definition and methods to quantify project complexity. It found that many researchers have aimed at characterising complexity using different project aspects and various indicators. However, there is a need to evaluate these indicators from the particular perspective of energy megaprojects, and to propose a standard terminology to describe project complexity. Chapter 3 examined the effectiveness of existing PCA methods, coming to the conclusion that there is a lack of effective PCA tools specifically for use with megaprojects in the energy sector.

2. *To identify contributing project complexity indicators (PCIs) and establish a logical standard categorisation for them*

Chapter 5 described the process of compiling a list of PCIs through a comprehensive literature review and synthesis. A total of 50 information sources were identified and reviewed, including studies on megaprojects as well as general projects. Complexity indicators were identified from those publications and were recorded with a brief definition. Altogether 110 relevant indicators were identified, which were subsequently consolidated into 51, through a process of synthesis.

The chapter also presented the process of developing the taxonomy of project complexity indicators. The process consists of two interactive and iterative procedures: the top-down process helps to determine the higher-level groupings of the taxonomy hierarchy, e.g. levels 1 and 2 categories for both internal and external PCIs as well as level 3 of internal PCIs. The bottom-up process analyses the list of 51 PCIs to identify logical groups of related indicators and link the groups to the higher-level categories. The top-down analysis followed the principles of the PRINCE2 project management standard. At the first level, two categories distinguish indicators within the project (internal) from those outside it (external). The external category involves 10 PCIs divided into five sub-categories (level 2): environmental, political, legal and regulatory, economic and social aspects. In the internal category, 41 internal indicators are grouped into three sub-categories in level 2 and ten in level 3 as follows:

- “Project characteristics” involves two sub-categories: technical characteristics and project objectives.
- “Project delivery organisation/team” includes four sub-categories: people, disciplines, capital and physical resources.
- “Process of delivery” contains four sub-categories: tasks, information, tools and methods, and time.

3. *To establish the relative importance and weight of each project complexity indicator when assessing the overall complexity of a project*

After identifying the PCIs and structuring them into a taxonomy, the study went on to establish the weight that should be attributed to each indicator when assessing the overall complexity of an energy megaproject. An integrated Delphi-AHP method was used involving two groups of experts: academics and professionals. The two major challenges were ensuring consistency of individual judgments and achieving consensus among the experts. A detailed description of this process was presented in Chapter 6. Based on input from the 20 experts, after two rounds of the Delphi-AHP method, consolidated and global weights of all PCIs were calculated, information which can be used as a good basis for assessing energy megaprojects. Furthermore, three different weighting scenarios were explored where the judgments of different experts are given different weights according to their profession and level of expertise.

4. To define numerical scoring criteria for all project complexity indicators

Another significant contribution of this study is defining Numerical Scoring Criteria (NSCs) for all PCIs. This is a prerequisite for the application of the developed PCA method in practice. Chapter 7 explained the process and main rationale for defining these NSCs. A synthetic review and analysis of the literature sources obtained explicit criteria for 33 PCIs. Then, an interpretive analysis defined the objective criteria for the remaining 18 PCIs. A 1-5 Likert scale was used to determine numerical thresholds for scoring the PCIs based on the objective criteria.

5. To evaluate the developed project complexity method

The developed PCA method was evaluated by expert review and tested through a case study.

- Expert review

  An expert review was conducted (Chapter 7) to assess the validity and appropriateness of the numerical scoring criteria. Nine experts participated in the expert review, involving three academics and six professionals, who have a high level of knowledge about megaprojects and the energy sector. Overall, the experts broadly supported and confirmed the NSCs; some suggestions were provided to improve the final NSCs.

- Case study

  To evaluate the applicability of the proposed PCA method, a case study was carried out with the development of two phases in an offshore gas field reservoir development programme. It demonstrated that the PCA method and tool can be used to assess the overall complexity of energy megaprojects. It also allows project teams to analyse the different factors contributing to project complexity. The example further showed that the PCA tool can be used to benchmark different projects in a programme portfolio and the project team can develop and implement specific management strategies to cope with complexities based on the assessment results.

9.3 Contribution to Knowledge

The PCA method developed in this study adds to the growing body of knowledge concerned with the issue of project complexity, from the particular perspective of megaprojects in the energy sector. Its contribution to knowledge includes both academic and practice domains.

9.3.1 *Academic perspective*

First, the research contributes to complex project management theory, by filling the gap left by a lack of comprehensive definition of project complexity; moreover, no study had previously addressed the particular problem of assessing project complexity in energy megaprojects. Rather than suggesting an explicit definition of project complexity, the study endeavours to define it by developing a taxonomy of 51 project complexity indicators, with a specific emphasis on megaprojects. The taxonomy provides a comprehensive framework to assess this type of project. The grouping of internal complexity indicators reflects common project management principles and exhibits more understanding compared with existing categorisation of project complexity in the literature. In recognition of the fact that external influencing factors, such as government policies and environment concerns, often play a crucial role in the success of energy megaprojects, the taxonomy also puts more emphasis on external complexity indicators, compared with previous studies. The hierarchy structure of taxonomy enables the objective evaluation of project complexity in different levels, macro and micro, which has not existed within many previous works.

The study establishes the relative importance and weights of PCIs by employing an innovative integrated Delphi-AHP method. Group decision-making methods are common tools for evaluating the importance of factors in project management; however, most of the studies have implemented either of these methods separately. Use of an integrated method can enhance efficiency because it benefits from the full potential of both methods, which can for example reduce the number of Delphi rounds. Furthermore, other studies have been limited by the use of simple numerical averages or multiplication of different levels, when calculating weights. This research employed a more robust mathematical method to obtain the consolidated and global weights of PCIs. This study also extended the mathematical method by developing a number of innovative enhancements, such as automatic consistency checking and scenario building.

The study fills another significant gap in the literature of project complexity, which is the lack of numerical criteria for evaluating the indicators. This gap were highlighted by Vidal (2009) and Bosch-Rekveldt (2011) as a critical addition to project complexity assessment methods. However, this issue does not appear to have been addressed by any research yet. The definition of scoring criteria for all complexity indicators constitutes a significant contribution of this study. These are specified as explicitly and objectively as possible to reduce the influence of subjectivity by the assessor(s). The defined criteria were reviewed and found adequate by experts. The taxonomy of 51 key project complexity indicators for energy megaprojects, and their numerical scoring criteria, provides a unique basis for the evaluation of project complexity.

9.3.2 *Practice perspective*

Practical application of research outcomes is at the centre of consideration for the development of the PCA method in this study. First, the taxonomy of PCIs provides a clear definition of project complexity for megaprojects, instead of trying to define project complexity with vague and difficult to understand terminology. Therefore, practitioners can effectively utilise this tool in their projects. The tool not only produces an overall complexity index, but also shows sources of complexity at detailed levels.

The PCA method was implemented in a spreadsheet, and tested through an energy megaproject case study. The complexity indices enable practitioners to develop management strategies geared to address specific complexity factors within the project. The tool can also be used to compare different projects, thereby supporting other decision-making during portfolio management. The PCA method could be of interest to project sponsors or different stakeholders of megaprojects, such as governments, professional associations or contractors. The developed PCA method can be employed in other energy megaprojects but can be tailored if necessary. The next section provides a guideline on how practitioners can use this thesis on their own projects.

9.4 A guideline on practical use of the developed PCA method

Since effective and practical use has been one of the ultimate goals of this research, it is important to outline different ways that the developed PCA method can be used by practitioners for the benefit of their projects:

1. One potential use of the research outcomes is to apply the taxonomy of project complexity indicators (Chapter 5) to project risk management. A direct consequence of increased project complexity is the increase in the level of project risks. Identification of potential risks is a prerequisite for managing them effectively. The developed taxonomy provides a comprehensive framework to review project risks, helping to avoid missing any important influencing factors. It can be used as a standalone tool during the risk management process, instead of as part of a project complexity assessment.

2. Practitioners can use the developed spreadsheet tool (Chapter 8) as an 'off-the-shelf' solution. They only need to score their particular project for all the project complexity indicators by applying the numerical scoring criteria devised by this study. The tool will calculate a complexity index for their projects by using the existing weights. While the weights established in this study may not be totally accurate for a specific project, they are reasonably realistic for the average energy megaprojects because they are defined based on inputs from 20 international experts in this field, who have built their experience and expertise on a wide range of projects. To use the tool in this way requires minimum extra effort from the practitioners. It is particularly useful to help practitioners quickly compare different options for one investment project or to compare different projects within a program portfolio.

3. In order to conduct more accurate complexity assessment, a project team can define their own weights for the PCIs following the methods

described in Chapter 6. Numerical scoring criteria can also be customised taking into account the capability of the project team in handling complexity. To use the PCA method in this way requires skills, which are beyond the normal expertise of practitioners. Assistance from experts may be required, who are familiar with the methods adopted by this research. Considering the size of typical energy megaprojects and the importance of a better understanding of their complexity, such a small investment may nonetheless be worthwhile for most megaprojects.

9.5 Research Limitations

Each research entails some limitations and this research is no exception. The limitations of this study are presented below:

- The scope of this study is limited to assessing project complexity. It does not cover the management of complexity or even cause-effect analysis of complexity. Although the case study showed that complexity assessment results can help project teams to develop appropriate management strategies, this aspect is outside the scope of this study. Therefore, there are no specific instructions on how the assessment results should be interpreted or acted on.
- Ideally, there should be a comprehensive evaluation of the existing complexity assessment practice in large energy companies. Unfortunately, due to commercial confidentiality, access to such information was not possible. This study can only adopt a preliminary investigation through interviews with professionals as a remedial measure.
- The important goal of establishing weights for PCIs was achieved with the help of 20 international experts. Although the adopted process is robust from a research perspective, the outcome is dependent on the experts' selection. Different groups of experts may produce different results. In fact, it can be argued that the weights produced by this study should only be considered as sound default values, each megaproject team should use the same method to produce weights that are more appropriate to their project conditions.

- The study considers PCIs as independent factors. In reality, there are many potential interactions and interrelationships between some of these factors. These were not considered in this study.
- This study largely adopted an approach of descriptive complexity; although some elements of perceived complexity were included when defining NSC. There is a need for more consideration of the balance between these two approaches.
- The implemented spreadsheet tool is relatively simplistic in its function. It only supports complexity assessment in a single user mode. In reality, such an assessment would usually involve a group of participants, each of whom focuses on certain aspects of the project. There is a need to expand the spreadsheet tool to support this type of group decision-making practice.

9.5 Future Research

On the basis of this study, a number of potential research topics can be studied further.

- This study has developed a PCA method but does not propose any management strategies to cope with the identified complexities. One possible direction of future investigation is to focus on the interpretation of the computed level of project complexity and develop management strategies appropriate for different levels of complexity. One way of doing this is through applying the PCA method retrospectively to a number of previous projects. Effort is also needed to collect information on management measures adopted for these projects. Cross-case analysis would help to establish the appropriateness and effectiveness of these measures. Such a study would lead to a best practice guide on project complexity management strategies that can be used in conjunction with this PCA method.

- PCIs in this research are considered independent factors. However, in reality some of them may be related in certain ways. Therefore, another perspective of future work is to investigate the interdependences between the PCIs in order to calculate more accurately the impact of each PCI on project complexity. Such a study can start with a cluster analysis of existing questionnaire data, supplementing them with addition survey data if necessary. The aim of the analysis is to establish a new typology of indicators based on their relations. Then, the ANP (Analytic Network Process) method can be used to produce new weights for PCIs. As discussed in the literature review, project complexity can be investigated by trying to understand its essence, i.e. the inner working mechanism of project elements and their dynamic interactions. Considering the interdependences between the PCIs as proposed here could be seen as a form of analysis of project (descriptive) elements and their interaction, which would add some sort of measure of the essence of complexity to our approach based on the study of factors impacting complexity. However, while such a study could lead to a more accurate calculation method for project complexity, the number of experts needed would increase, which would make it more difficult to implement.

- Section 9.4 outlined three ways for the practical use of the PCA method from a practitioner's perspective. The project specific application (the third option) requires the support of an expert, who is familiar with the methods used in this study. Another possible direction of future research is to develop a knowledge-based system, which can provide user-friendly advice for practitioners. Such a system would enable them to follow the methodology of this study in order to produce weights and scoring criteria which are more appropriate to their project.

- Section 9.5 highlighted one of the limitations of this study in the single-user nature of the PCA tool. Future research can expand it to a multi-user application with an underlying support of a group decision-making methodology. Such a study would need to investigate the process of project complexity assessment in practice and identify the key participants and their roles. Then, it would require developing an IT system to support the effective implementation of project complexity assessment with the participation of multiple practitioners.

References

Accenture’s Innovation Center for Energy and Utilities, 2012. *Capital Project Delays and Budget Overruns Could Cost Oil and Gas and Utility Industries Trillions of Dollars*, Available at: *http://www.accenture.com*

Adler, M. & Ziglio, E., 1996. *Gazing Into the Oracle: The Delphi Method and Its Application to Social Policy and Public Health*, Jessica Kingsley Publishers.

Aguarón, J., Escobar, M.T. & Moreno-Jiménez, J.M., 2003. Consistency stability intervals for a judgement in AHP decision support systems. *European Journal of Operational Research*, 145(2), pp.382–393.

Aguarón, J. & Moreno-Jiménez, J.M., 2003. The geometric consistency index: Approximated thresholds. *European Journal of Operational Research*, 147(1), pp.137–145.

Aitken, A. & Crawford, L., 2007. A study of project categorisation based on project management complexity. In *IRNOP VIII*.

Al-Hajri, H.M., 2006. *An Exploratory Study on Information System Development Methodologies Adoption: Utilizing Delphi Technique and Analytical Hierarchy Process*. University of Salford.

Al-Harbi, K.M.A.-S., 2001. Application of the AHP in project management. *International Journal of Project Management*, 19(1), pp.19–27.

Alharbi, M., Emmitt, S. & Demian, P., 2015. Transferring architectural management into practice: A taxonomy framework. *Frontiers of Architectural Research*.

APMG, 2013. *APMG Maturity Index*, Available at: *http://www.apmg-international.com/nmsruntime/saveasdialog.aspx?lID=5476&sID=5851*

Austin, S., Newton, A., Steele, J. & Waskett, P., 2002. Modelling and managing project complexity. *International Journal of Project Management*, 20(3), pp.191–198.

Azadeh, A., Keramati, A. & Jafary Songhori, M., 2009. An integrated Delphi/VAHP/DEA framework for evaluation of information technology/information system (IT/IS) investments. *The International Journal of Advanced Manufacturing Technology*, 45(11-12), pp.1233–1251.

Babic, Z. & Plazibat, N., 1998. Ranking of enterprises based on multicriterial analysis. *International Journal of Production Economics*, 56-57, pp.29–35.

Baccarini, D., 1996. The concept of project complexity—a review. *International Journal of Project Management*, 14(4), pp.201–204.

Bana Costa, C.A. & Vansnick, J.-C., 2008. A critical analysis of the eigenvalue method used to derive priorities in AHP. *European Journal of Operational Research*, 187(3), pp.1422–1428.

Barlow, J., 2000. Innovation and learning in complex offshore construction projects. *Research Policy*, 29(7-8), pp.973–989.

Beccali, M., Cellura, M. & Ardente, D., 1998. Decision making in energy planning: the ELECTRE multicriteria analysis approach compared to a FUZZY-SETS methodology. *Energy Conversion and Management*, 39(16-18), pp.1869–1881.

Belton, V. & Gear, T., 1983. On a short-coming of Saaty's method of analytic hierarchies. *Omega*, 11(3), pp.228–230.

Benbya, H. & McKelvey, B., 2006. Toward a complexity theory of information systems development E. Jacucci, ed. *Information Technology & People*, 19(1), pp.12–34.

Benjelloun, A., Crainic, T.G. & Bigras, Y., 2010. Towards a taxonomy of City Logistics projects. *Procedia - Social and Behavioral Sciences*, 2(3), pp.6217–6228.

Birol, F., 2006. World Energy Prospects and Challenges. *Australian Economic Review*, 39(2), pp.190–195.

Bosch-Rekveldt, M., Jongkindb Y., Mooia, H., Bakkerc, H. & Verbraeck, A., 2011. Grasping project complexity in large engineering projects: The TOE (Technical, Organizational and Environmental) framework. *International Journal of Project Management*, 29(6), pp.728–739.

Bosch-Rekveldt, M., 2011. *Managing project complexity A study into adapting early project phases to improve project performance in large engineering projects*. Delft University of Technology.

Bosch-Rekveldt, M. & Mooi, H., 2008. Research into Project Complexity Classification Methods. In *IPMA 22nd World Congress*. pp. 104–108.

Brans, J.P., 1982. Lingenierie de la decision. Elaboration dinstruments daide a la decision. Methode PROMETHEE. In *Laide a la Decision: Nature, Instrument s et Perspectives Davenir*. Presses de Universite Laval, pp. 183–214.

Brockmann, C. & Girmscheid, G., 2007. Complexity of Megaprojects. In *CIB World Building Congress*.

Brooks, N., 2013. *Emergent Cross-Case and Cross-Sectoral Themes from the Megaproject Portfolio*, COST Megaproject, Available at: *http://www.mega-project.eu/resources/view/emergent-cross-case-and-cross-sectoral-themes-from-the-megaproject-portfoli*

Bruijn, H. & Leijten, M., 2007. Megaprojects and Contested Information. *Transportation Planning and Technology*, 30(1), pp.49–69.

Bryman, A., 2012. *Social Research Methods*, OUP Oxford.

Bryman, A. & Bell, E., 2011. *Business Research Methods*, OUP Oxford.

De Camprieu, R., Desbiens, J. & Feixue, Y., 2007. "Cultural" differences in project risk perception: An empirical comparison of China and Canada. *International Journal of Project Management*, 25(7), pp.683–693.

Cantarelli, C.C., Flyvbjerg, B. & Buhl, S.L., 2012. Geographical variation in project cost performance: the Netherlands versus worldwide. *Journal of Transport Geography*, 24, pp.324–331.

Capka, R., 2004. Megaprojects – They are a different breed. *Public roads, U.S. Department of Transportation*, 68(1).

Cavallaro, F., 2005. An Integrated Multi-Criteria System to Assess Sustainable Energy Options: An Application of the Promethee Method. *SSRN Electronic Journal*.

Chatterji, M., 1997. *Regional science perspectives for the future*, NY: Palgrave Macmillan.

Cheng, E.W.L., Li, H. & Ho, D.C.K., 2002. Analytic hierarchy process (AHP). *Measuring Business Excellence*, 6(4), pp.33–37.

Chiclana, F., Mata, F., Martinez, L., Herrera-Viedma, E. & Alonso, S., 2008. Integration of a Consistency Control Modile Within a Consensus Model. *International Journal of Uncertainty, Fuzziness and Knowledge-Based Systems*, 16(1), pp.35–53.

Chu, A.T.W., Kalaba, R.E. & Spingarn, K., 1979. A comparison of two methods for determining the weights of belonging to fuzzy sets. *Journal of Optimization Theory and Applications*, 27(4), pp.531–538.

Cicmil, S., Terry, C.-D. & Lynn, C., 2009. *Exploring the Complexity of Projects: Implications of Complexity Theory for Project Management Practice*, PMI, Newtown Square, PA.

Clift, T.B. & Vandenbosch, M.B., 1999. Project Complexity and Efforts to Reduce Product Development Cycle Time. *Journal of Business Research*, 45(2), pp.187–198.

Collis, J. & Hussey, R., 2013. *Business Research: A Practical Guide for Undergraduate and Postgraduate Students*, NY: Palgrave Macmillan.

Cooke-Davies, T.J. Cicmil, S., Crawford, L. & Richardson, K., 2007. We're not in Kansas anymore, Toto: Mapping the strange landscape of complexity theory, and its relationship to project management. *Project management journal*, 38(2), pp.50–61.

Crawford, G. & Williams, C., 1985a. A note on the analysis of subjective judgment matrices. *Journal of Mathematical Psychology*, 29(4), pp.387–405.

Crawford, G. & Williams, C., 1985b. A note on the analysis of subjective judgment matrices. *Journal of Mathematical Psychology*, 29(4), pp.387–405.

Creswell, J.W., 2009. *Research design : qualitative, quantitative, and mixed methods approaches.*, London: SAGE Publications.

Dalkey, N. & Helmer, O., 1963. An Experimental Application of the DELPHI Method to the Use of Experts.

Davies, A. & Brady, T., 2000. Organisational capabilities and learning in complex product systems: towards repeatable solutions. *Research Policy*, 29(7-8), pp.931–953.

Davies, E.M., 1973. An experimental investigation of resource allocation in multiactivity projects. *Operational Research Quarterly*, 24(4), pp.587–591.

Davis, E.W., 1975. Project Network Summary Measures Constrained-Resource Scheduling. *AIIE Trans*, 7(2), pp.132–142.

Delbecq, A.L., de Ven, A.H. & Gustafson, D.H., 1975. *Group techniques for program planning: a guide to nominal group and Delphi processes*, Scott, Foresman.

Dimitriou, H.T., Ward, E.J. & Wright, P.G., 2012. *Mega Projects Executive Summary Lessons for Decision-maker,*

DMO, 2006. *Acquisition Categorisation Framework - Policy for the Categorisation of Projects*, Canberra: Australia Government.

DTIOG, 2001. *Top ten management issues* PT-2001st–01 ed., Washington, DC: U.S. Dept. of Transportation.

Dunović, I.B., Radujković, M. & Škreb, K.A., 2014. Towards a New Model of Complexity – The Case of Large Infrastructure Projects. *Procedia - Social and Behavioral Sciences*, 119, pp.730–738.

Dvir, D., Sadeh, A. & Malach-Pines, A., 2006. Projects and project managers: the relationship between project manager's personality, project, project types, and project success. *Project Management Journal*, 37(5), pp.36–48.

Easterby-Smith, M., Thorpe, R. & Lowe, A., 1991. *Management research : an introduction*, London: SAGE Publications.

EY, 2014. *Spotlight on oil and gas megaprojects*, Available at: *http://www.ey.com/Publication/vwLUAssets/EY-spotlight-on-oil-and-gas-megaprojects/$FILE/EY-spotlight-on-oil-and-gas-megaprojects.pdf*

Fayek, A.R., Yorke, M. & Cherlet, R., 2011. Workforce training initiatives for megaproject success. *Canadian Journal of Civil Engineering*.

Feldman, E.J., 1985. *Patterns of failure in government megaprojects : economics, politics, and participation in industrial democracies*, Harvard and University press of America, Cambdridge, MA.

Figueira, J., Greco, S. & Erghott, M., 2005. *Multiple Criteria Decision Analysis: State of the Art Surveys*, Berlin: Springer.

Fioretti, G. & Visser, B., 2004. A cognitive interpretation of organizational complexity. *Emergence: Complexity & Organization*, 6(1), pp.11–23.

Fiori, C. & Kovaka, M., 2005. Defining megaprojects: Learning from construction at the edge of experience. *Proceedings of Research Congress, ASCE,* (480).

Flyvbjerg, B., 2014. *Megaproject planning and management: essential readings*, London: Edward Elgar Publishing.

Flyvbjerg, B., 2009. What is a Megaproject? Available at: http://flyvbjerg.plan.aau.dk/whatisamegaproject.php.

Flyvbjerg, B., Bruzelius, N. & Rothengatter, W., 2003. *Megaprojects and Risk: An Anatomy of Ambition*, Cambridge University Press.

Flyvbjerg, B. & Stewart, A., 2012. Olympic Proportions: Cost and Cost Overrun at the Olympics 1960-2012. *SSRN Electronic Journal*.

Georgopoulou, E., Lalas, D. & Papagiannakis, L., 1997. A multicriteria decision aid approach for energy planning problems: The case of renewable energy option.

European Journal of Operational Research, 103(1), pp.38–54.

Geraldi, J. & Adlbrecht, G., 2007. On faith, fact and interaction in projects. *Project Management Journal*, 38(1), pp.32–43.

Geraldi, J., Maylor, H. & Williams, T., 2011. Now, let’s make it really complex (complicated). *International Journal of Operations & Production Management*, 31(9), pp.966–990.

Ghauri, P. & Gronhaug, K., 2001. *Research Methods in Business Studies : A Practical Guide*, Harlow: Financial Times Prentice Hall.

Gidado, K.I., 1996. Project complexity: The focal point of construction production planning. *Construction Management and Economics*, 14(3), pp.213–225.

Giezen, M., 2012a. Keeping it simple? A case study into the advantages and disadvantages of reducing complexity in mega project planning. *International Journal of Project Management*, 30(7), pp.781–790.

Giezen, M., 2012b. Keeping it simple? A case study into the advantages and disadvantages of reducing complexity in mega project planning. *International Journal of Project Management*, 30(7), pp.781–790.

Global Alliance for Project Performance Standards, 2007. *A Framework for Performance Based Competency Standards for Global Level 1 and 2 Project Managers*, Available at: *http://globalpmstandards.org/wp-content/uploads/2014/12/GAPPS_Project_Manager_v1.1150411_A4.pdf*

Gransberg, D.D. Shane, J., Strong, K., & del Puerto, C., 2013. Project Complexity Mapping in Five Dimensions for Complex Transportation Projects. *Journal of Management in Engineering*, 29(4), pp.316–326.

Greiman, V.A., 2013. *Megaproject Management: Lessons on Risk and Project Management from the Big Dig*, NY: John Wiley & Sons.

Grün, O., 2004. *Taming giant projects: Management of multi-organization enterprises. Berlin: Springer*, Berlin: Springer.

Hall, P., 1982. *Great planning disasters*, University of california Press, CA.

Hämäläinen, R.P., 1990. A decision aid in the public debate on nuclear power. *European Journal of Operational Research*, 48(1), pp.66–76.

Haralambopoulos, D.A. & Polatidis, H., 2003. Renewable energy projects: structuring a multi-criteria group decision-making framework. *Renewable Energy*, 28(6), pp.961–973.

Hass, K., 2007. Introducing the project complexity model - A new approach to diagnosing and managing projects. *PM World Today*, IX(VII), pp.1–8.

Hass, K., 2009. *Managing Complex Projects, A New Model*, Vienna: Management Concepts Inc., 2009.

Hassan, T., Mccaffer, R. & Thorpe, T., 1999. Emerging clients' needs for Large Scale Engineering projects. *Engineering, Construction and Architectural Management*, 6(1), pp.21–29.

Hasson, F. & Keeney, S., 2011. Enhancing rigour in the Delphi technique research. *Technological Forecasting and Social Change*, 78(9), pp.1695–1704.

Haynes, W., 2005. Transportation at the Millennium: In Search of a Megaproject Lens. *Review of Policy Research*, 19(2), pp.62–64.

He, Q., Luo, L., Hu, Y. & Chan, A., 2015. Measuring the complexity of mega construction projects in China—A fuzzy analytic network process analysis. *International Journal of Project Management*, 33(3), pp.549–563.

Helmsman Institute, 2011. *Complexity Assessment of Australia's Defence Projects*, Available at: *http://www.helmsman-institute.com/sites/institute/PDF/HelmsmanDefenceProjectComplexityReport.pdf*

Helmsman Institute, 2009. *Helmsman Guide to Complexity*, Available at: *http://www.helmsman-institute.com/sites/institute/PDF/Helmsman%20Guide%20to%20Complexity.pdf*

Herrera-Viedma, E., Martinez, L., Mata, F. & Chiclana, F., 2005. A Consensus Support System Model for Group Decision-Making Problems With Multigranular Linguistic Preference Relations. *IEEE Transactions on Fuzzy Systems*, 13(5), pp.644–658.

Herrera-Viedma, E., Martinez, L., Mata, F. & Chiclana, F., 2007. Group Decision-Making Model With Incomplete Fuzzy Preference Relations Based on Additive Consistency. *IEEE Transactions on Systems, Man and Cybernetics, Part B (Cybernetics)*, 37(1), pp.176–189.

Herrera-Viedma, E., Herrera, F. & Chiclana, F., 2002. A consensus model for multiperson decision making with different preference structures. *IEEE Transactions on Systems, Man, and Cybernetics - Part A: Systems and Humans*, 32(3), pp.394–402.

Hertogh, M., Baker, S., Staal-Ong, P. & Westerveld, E., 2008. *Managing Large Infrastructure Projects. Research on Best Practices and Lessons Learnt in Large Infrastructure Projects in Europe*, Bennebroek: AT Osbourne.

Hobday, M., Rush, H. & Tidd, J., 2000. Innovation in complex products and system. *Research Policy*, 29(7-8), pp.793–804.

Holsapple, C.W. & Joshi, K.D., 2002. Knowledge manipulation activities: results of a Delphi study. *Information & Management*, 39(6), pp.477–490.

Hu, Y. Chan, A., Le, Y., & Jin, R., 2014. From Construction Megaproject Management to Complex Project Management: Bibliographic Analysis. *Journal of Management in Engineering*, p.04014052.

Huang, Y.-S., Liao, J.-T. & Lin, Z.-L., 2009. A study on aggregation of group decisions. *Systems Research and Behavioral Science*, 26(4), pp.445–454.

Huselid, M.A., 1995. The impact of human resource management practices on turnover, productivity, and corporate financial performance. *Academy of Management Journal*, 38(3), pp.635–672.

Hussey, J. & Hussey, R., 1997. *Business Research : A Practical Guide for Undergraduate and Postgraduate Students*, Basingstoke: Macmillan.

Hwang, C.-L. & Lin, M.-J., 1987. *Group Decision Making under Multiple Criteria*, Berlin: Springer.

Hwang, C.L. & Yoon, K., 1981. *Multiple Attributes Decision Making Methods and Applications*, Berlin: Springer.

Internationa Energy Agency, 2006. *World Energy outlook 2006*, Available at: *http://www.worldenergyoutlook.org/media/weowebsite/2008-1994/weo2006.pdf*

IPMA, 2013. *IPMA Competence Baseline: ICB*, Available at: *http://www.ipma.world/resources/ipma-publications/ipma-competence-baseline/*

IPMA, 2010. *IPMA Competence Baseline: ICB*, International Project Management Association Press.

Ishizaka, A. & Labib, A., 2011. Review of the main developments in the analytic hierarchy process. *Expert Systems with Applications*, 38(11), pp.14336–14345.

Ishizaka, A. & Lusti, M., 2004. An expert module to improve the consistency of AHP matrices. *International Transactions in Operational Research*, 11(1), pp.97–105.

Ishizaka, A. & Lusti, M., 2006. How to derive priorities in AHP: a comparative study. *Central European Journal of Operations Research*, 14(4), pp.387–400.

Jaafari, A., 2003. Project management in the age of complexity and change. *Project Management Journal*, 34(4), pp.47–57.

Jain, B.A. & Nag, B.N., 1996. A decision-support model for investment decisions in new ventures. *European Journal of Operational Research*, 90(3), pp.473–486.

Jiang, L., Qi, E.-S. & Du, B., 2008. Study of the Characteristics of Large-Scale Construction Projects with the Viewpoint of Complexity. In *2008 4th International Conference on Wireless Communications, Networking and Mobile Computing*. IEEE, pp. 1–4.

Jiang, W., Li, Y. & Qinghua, H., 2009. A review on organization management of large-scale complex projects. *Project Management Technology*, (12), pp.20–24.

Johnson, C.R., Beine, W.B. & Wang, T.J., 1979. Right-left asymmetry in an eigenvector ranking procedure. *Journal of Mathematical Psychology*, 19(1), pp.61–64.

Kaimann, R.A., 1974. Coefficient of Network Complexity. *Management Science*, 21(2172-177).

Karapetrovic, S. & Rosenbloom, E.S., 1999. A quality control approach to consistency paradoxes in AHP. *European Journal of Operational Research*, 119(3), pp.704–718.

Kardes, I., Ozturkb, A. & Cavusgil, S., 2013. Managing global megaprojects: Complexity and risk management. *International Business Review*, 22(6), pp.905–917.

Katzenbach, J.R. & Smith, D.K., 1992. *The Wisdom of Teams: Creating the High-Performance Organization*, Harvard Business Review Press.

Kendall, M.G., 1955. Further Contributions to the Theory of Paired Comparisons. *Biometrics*, 11(1), pp.43–62 CR – Copyright © 1955 International Bi.

Kendall, M.G. & Smith, B.B., 1940. On the Method of Paired Comparisons. *Biometrika*, 31(3/4), pp.324–345 CR – Copyright © 1940 Biometrika Tru.

Kian Manesh Rad, E. & Sun, M., 2014. Taxonomy of Poject Complexity Indicators in Energy Megaprojects. In *People, Buildings and Environment an international scientific conference, Czech Republic*.

Kiker, G.A., Bridges, S., Varghese, A., Seager, T. & Linkov, I., 2005. Application of Multicriteria Decision Analysis in Environmental Decision Making. *Integrated Environmental Assessment and Management*, 1(2), p.95.

Klakegg, O.J., Williams, T. & Magnussen, O., 2008. Governance frameworks for public project development and estimation. *Project Management Journal*, 39(S1), pp.S27–S42.

Kohli, U., 2006. *Project Management Handbook*, London: McGraw-Hill.

Korpela, J. & Tuominen, M., 1996. A decision aid in warehouse site selection. *International Journal of Production Economics*, 45(1-3), pp.169–180.

Koster, K., 2009. *International Project Management*, London: SAGE Publications.

Krishnaswamy, K.N. & Sivakumar, A.I., 2009. *Management Research Methodology: Integration of Methods and Techniques*, Pearson Education.

Kuenz Murphy, C., 1993. Limits on the analytic hierarchy process from its consistency index. *European Journal of Operational Research*, 65(1), pp.138–139.

Lane, R., Lepardo, V. & Woodman, G., 2002. How to Deal with Dynamic Complexity on Large, Long Projects. In *Designing, Constructing, Maintaining, and Financing Today's Airport Projects*. American Society of Civil Engineers, pp. 1–10.

Latva-Koivisto, A.M., 2001. *Finding a complexity measure for business process models*, Systems Analysis Laboratory, Helsinki University of Technology Press.

Lebcir, M. & Choudrie, J., 2011. A dynamic model of the effects of project complexity on time to complete construction projects. *International Journal of Innovation Management*, 6(2), pp.477–483.

Les Van Der Lei, T.E., Kolfschoten, G.L. & Beers, P.J., 2010. Complexity in multi-actor system research: towards a meta-analysis of recent studies. *Journal of Design Research*, 8(4), pp.317 – 342.

Lessard, D., Sakhrani, V. & Miller, R., 2014. House of Project Complexity—understanding complexity in large infrastructure projects. *Engineering Project Organization Journal*, 4(4), pp.170–192.

Linstone, H.A. & Turoff, M., 1975. *The Delphi Method: Techniques and Applications*,

Littau, P., 2013. *Managing Stakeholders in Megaprojects*, Available at: *http://www.mega-project.eu/assets/exp/docs/Managing_Stakeholders_in_Megaprojects.pdf*

Little, G., Tuttle, R., Clark, D. & Corney, J., 1998. A feature complexity index. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science* , 212 (5), pp.405–412.

Little, T., 2005. Context-Adaptive Agility: Managing Complexity and Uncertainty. *IEEE Software*, 22(3), pp.28–35.

Liu, B., Shenb, Y., Chena, Y., Chenc, X. & Wang, Y., 2015. A two-layer weight determination method for complex multi-attribute large-group decision-making experts in a linguistic environment. *Information Fusion*, 23, pp.156–165.

Lloyd, S., 2006. *Programming the Universe*, Berlin: Knopf.

Locatelli, G., Littau, P., Brookes, N.J. & Mancini, M., 2014. Project Characteristics Enabling the Success of Megaprojects: An Empirical Investigation in the Energy Sector. *Procedia - Social and Behavioral Sciences*, 119, pp.625–634.

Locatelli, G. & Littau, P., 2013. *Closing Report on the Research Activities of the Energy Working Group*,COST Megaprojects, Available at: *http://www.mega-project.eu/assets/exp/resources/Final_Report_Energy_Group_GL_5.0.pdf*

Locatelli, G. & Mancini, M., 2012. A framework for the selection of the right nuclear power plant. *International Journal of Production Research*, 50(17), pp.4753–4766.

Locatelli, G. & Mancini, M., 2013. *Flamanville 3 Nuclear Power Plant*, COST Megaprojects, Available at: *http://www.mega-project.eu/assets/exp/resources/Flamanville_NPP_V02.pdf*

Lu, Y., Luo, L., Wang, H., Lea, L. & Shi, Q., 2014. Measurement model of project complexity for large-scale projects from task and organization perspective. *International Journal of Project Management*, 33(3), pp.610–622.

Major projects association, 2014. *Making major projects bankable*, London.

Major Projects Authority, 2012. *Project Assessment Review: MPA Guidance for Departments*, Available at: *https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/61378/MPA_20PAR_20guidance_20for_20Departments.pdf*

Mancini, M., 2013. *An STSM to Dubrovnik in October 2013 to research Megaproject Stakeholder Management Success*, Available at: *http://www.mega-project.eu/resources/view/mauro-mancini-stsm-report-oct-2013*

Mangan, J., Lalwani, C. & Gardner, B., 2013. Combining quantitative and qualitative methodologies in logistics research. *International Journal of Physical Distribution*

& Logistics Management.

Marradi, A., 1990. Classification, Typology, Taxonomy. *Quality & Quantity*, 24, pp.129–157.

Martin, A. & Pierre-Alain, J., 2004. *A Framework. for Quantifying Complexity and Understanding its Sources: Application to two Large-Scale Systems*. Massachusetts Institute of Technology.

Martin, P., 2004. *Framework. for Quantifying Complexity and Understanding its Sources: Application to two Large-Scale Systems*, Massachusetts Institute of Technology.

Maylor, H., Vidgen, R. & Carver, S., 2008. Managerial complexity in project-based operations: A grounded model and its implications for practice. *Project Management Journal*, 39(S1), pp.S15–S26.

Mendoza, M.A., 2015. Reinsurance as Governance: Governmental Risk Management Pools as a Case Study in the Governance Role Played by Reinsurance Institutions.

Merrow, E., 2012. Oil and Gas Industry Megaprojects: Our Recent Track Record. *Oil and Gas Facilities*, (September 2011), pp.38–42.

Merrow, E.W., 2011. *Industrial Megaprojects: Concepts, Strategies, and Practices for Success*, London: Wiley.

Miller, R. & Lessard, D., 2001. *The Strategic Management of Large Engineering Projects: Shaping Institutions, Risks and Governance*, The MIT press.

Morel, B. & Ramanujam, R., 1999. Through the Looking Glass of Complexity: The Dynamics of Organizations as Adaptive and Evolving Systems. *Organization Science*, 10(3), pp.278–293.

Moreno-Jiménez, J.M., Aguarón, J. & Escobar, M.T., 2007. The Core of Consistency in AHP-Group Decision Making. *Group Decision and Negotiation*, 17(3), pp.249–265.

Mousavi, S.M., Tavakkoli-Moghaddam, R., Heydar, M. & Ebrahimnejad, S., 2012. Multi-Criteria Decision Making for Plant Location Selection: An Integrated Delphi–AHP–PROMETHEE Methodology. *Arabian Journal for Science and Engineering*, 38(5), pp.1255–1268.

Nassar, K.M. & Hegab, M.Y., 2006. Developing a Complexity Measure for Project Schedules. *Journal of Construction Engineering and Management*, 132(6), pp.554–561.

National Audit Office, 2012. *Modernizing Construction*, Available at: *https://www.nao.org.uk/report/modernising-construction/*

Nguyen, A.T., Nguyenb, L., Le-Hoaic, L. & Dangd, C., 2015. Quantifying the complexity of transportation projects using the fuzzy analytic hierarchy process. *International Journal of Project Management*, 33(6), pp.1364–1376.

Nijhuis, S.A., Vrijhoef, R. & Kessels, J.W.M., 2015. Towards a Taxonomy for Project Management Competences. *Procedia - Social and Behavioral Sciences*, 194, pp.181–191.

Nowak, M., 2005. Investment projects evaluation by simulation and multiple criteria decision aiding procedure. *Journal of Civil Engineering and Management*, 11(3), pp.193–202.

Oates, B.J., 2006. *Researching Information Systems and Computing*, London: SAGE Publications.

Office of Government Commerce, 2009. *Managing Successful Projects with PRINCE2*, Stationery Office Books.

Okoli, C. & Pawlowski, S.D., 2004. The Delphi method as a research tool: an example, design considerations and applications. *Information & Management*, 42(1), pp.15–29.

Opricovic, S. & Tzeng, G.-H., 2004. Compromise solution by MCDM methods: A comparative analysis of VIKOR and TOPSIS. *European Journal of Operational Research*, 156(2), pp.445–455.

Owens, J., Ahn, J., Shane, J., Strong, K. & Gransberg, D., 2011. Defining Complex Project Management of Large U.S. Transportation Projects: A Comparative Case Study Analysis. *Public Works Management & Policy*, 17(2), pp.170–188.

Parolia, N., Jiangb, J., Kleinc, G. & Sheu, T., 2011. The contribution of resource interdependence to IT program performance: A social interdependence perspective. *International Journal of Project Management*, 29(3), pp.313–324.

Paterson, R., 2006. More on Complex versus Complicated. Available at: *http://smartpei.typepad.com/robert_patersons_weblog/2006/11/more_on_complex.html.*

Pitt, L.F., Watson, R.T. & Kavan, C.B., 1995. Service Quality: A Measure of Information Systems Effectiveness. *MIS Quarterly*, 19(2), pp.173–187.

Pohekar, S.D. & Ramachandran, M., 2004. Application of multi-criteria decision making to sustainable energy planning—A review. *Renewable and Sustainable Energy Reviews*, 8(4), pp.365–381.

Pöyhönen, M.A., Hämäläinen, R.P. & SALO, A.A., 1997. An Experiment on the Numerical Modelling of Verbal Ratio Statements. *Journal of Multi-Criteria Decision Analysis*, 6(1), pp.1–10.

Priemus, H., Flyvbjerg, B. & Wee, B., 2008. *Decision-making on Mega-projects: Cost-benefit Analysis, Planning and Innovation*, Cheltenham: Edward Elgar Publishing Ltd.

Procaccini, C., Lea-Cox, A. & Scheffer, W. de H., 2012. Challenges of E & P Megaproject Delivery. Available at: *http://www.sbc.slb.com/Our_Ideas/Energy_Perspectives/Summer12_Content/Summer 12_Challenges.aspx.*

Project Management Institute, 2014. *Navigating Complexity: A Practice Guide*, PMI, Newtown Square, PA.

Pryke, S. & Smyth, H., 2006. *The Management of Complex Projects: a relationship approach*, Oxford: Blackwell.

Quinlan, C., 2011. *Business Research Method*, Colon: Cengage Learning EMEA.

Qureshi, S.M. & Kang, C., 2015. Analysing the organizational factors of project complexity using structural equation modelling. *International Journal of Project Management*, 33(1), pp.165–176.

Ramanathan, R., 1997. A note on the use of goal programming for the multiplicative AHP. *Journal of Multi-Criteria Decision Analysis*, 6(5), pp.296–307.

Ramanathan, R. & Ganesh, L.S., 1995. Energy resource allocation incorporating qualitative and quantitative criteria: An integrated model using goal programming and AHP. *Socio-Economic Planning Sciences*, 29(3), pp.197–218.

Rauch, W., 1979. The decision Delphi. *Technological Forecasting and Social Change*, 15(3), pp.159–169.

Remington, K. & Pollack, J., 2007. *Tools for Complex Projects*, NY: Gower.

Remington, K., Zolin, R. & Turner, R., 2009. A model of project complexity : distinguishing dimensions of complexity from severity. *Proceedings of the 9th International Research Network of Project Management Conference*.

Ribbers, P.M.A. & Schoo, K.-C., 2002. Program Management and Complexity of ERP

Implementations. *Engineering Management Journal*, 14(2), pp.45–52.

Ribeiro, R.A., 1996. Fuzzy multiple attribute decision making: A review and new preference elicitation techniques. *Fuzzy Sets and Systems*, 78(2), pp.155–181.

Roy, B. & Vanderpooten, D., 1997. An overview on “The European school of MCDA: Emergence, basic features and current works.” *European Journal of Operational Research*, 99(1), pp.26–27.

Saaty, T.L., 1977. A scaling method for priorities in hierarchical structures. *Journal of Mathematical Psychology*, 15(3), pp.234–281.

Saaty, T.L., 2003. Decision-making with the AHP: Why is the principal eigenvector necessary. *European Journal of Operational Research*, 145(1), pp.85–91.

Saaty, T.L., 1989. Group Decision Making and the AHP. *The Analytic Hierarchy Process*, pp.59–67.

Saaty, T.L., 1991. Response to Holder’s Comments on the Analytic Hierarchy Process. *The Journal of the Operational Research Society*, 42(10), pp.909–914 CR – Copyright © 1991 Operational Re.

Saaty, T.L., 1980. *The Analytic Hierarchy Process, Planning, Piority Setting, Resource Allocation*, New York: McGraw-Hill.

Saaty, T.L., 1990. *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*, RWS.

Salo, A.A. & Hämäläinen, R.P., 1997. On the measurement of preferences in the analytic hierarchy process. *Journal of Multi-Criteria Decision Analysis*, 6(6), pp.309–319.

Saunders, M., Lewis, P. & Thornhill, A., 2012. *Research Methods for Business Students*, Financial Times/ Prentice Hall.

Schlindwein, S.L. & Ison, R., 2004. Human knowing and perceived complexity: implications for systems practice. *Emergence: Complexity and Organization*, 6(3), pp.27–32.

Schmidt, R., Lyytinen, K., Keil, M. & Cule, P., 2001. Identifying Software Project Risks: An International Delphi Study. *Journal of Management Information Systems*, 17(4), pp.5–36.

Schmidt, R.C., 1997. Managing Delphi Surveys Using Nonparametric Statistical Techniques*. *Decision Sciences*, 28(3), pp.763–774.

Shafiei-Monfared, S. & Jenab, K., 2012a. A novel approach for complexity measure analysis in design projects. *Journal of Engineering Design*, 23(3), pp.185–194.

Shafiei-Monfared, S. & Jenab, K., 2012b. A novel approach for complexity measure analysis in design projects. *Journal of Engineering Design*, 23(3), pp.185–194.

Shannon, C.E., 1948. The mathematical theory of communication. *Bell Systems Technological Journal*, (27), pp.379–423.

Shehu, Z. & Akintoye, A., 2010. Major challenges to the successful implementation and practice of programme management in the construction environment: A critical analysis. *International Journal of Project Management*, 28(1), pp.26–39.

Shenhar, A.J. & Dvir, D., 1996. Toward a typological theory of project management. *Research Policy*, 25(4), pp.607–632.

Shenhar, J. & Dvir, D., 2007. *Reinventing project management: The diamond approach to successful growth and innovation*, Harvard Business School Press.

Shore, B. & Cross, B.J., 2005. Exploring the role of national culture in the management of large-scale international science projects. *International Journal of Project Management*, 23(1), pp.55–64.

Simon, H.A., 1962. The architecture of complexity. *Proceedings of the American Philosophical Society, 106(6): 467-482.*, 106(6), pp.467–482.

Sinha, S., Kumar, B. & Thomson, A., 2006. Measuring project complexity: A project manager's tool. *Architectural Engineering and Design Management*, 2, pp.187–202.

Sinha, S., Thomson, A.I. & Kumar, B., 2001. A complexity index for the design process. *WDK Publications*, pp.157–163.

Siraj, S., 2011. *Preference Elicitation from Pairwise Comparisons in Multi-Criteria Decision Making*. University of Manchester.

Skulmoski, G., Hartman, F. & Krahn, J., 2007. The Delphi method for graduate research. *Technology Education: Research*, 6.

Skulmoski, G.J., Hartman, F.T. & Krahn, J., 2006. The Delphi Method for Graduate Research. *Journal of Information Technology Education*, 6, pp.1–21.

Sommer, S.C. & Loch, C.H., 2004. Selectionism and Learning in Projects with Complexity and Unforeseeable Uncertainty. *Management Science*, 50(10), pp.1334–1347.

Sovacool, B.K. & Cooper, C.J., 2013. *The Governance of Energy Megaprojects: Politics, Hubris and Energy Security*, London: Edward Elgar Publishing, Incorporated.

Spector, M.D. & Jones, G.E., 2004. Trust in the workplace: factors affecting trust formation between team members. *The Journal of social psychology*, 144(3), pp.311–21.

Stam, A. & Duarte Silva, A.P., 2003. On multiplicative priority rating methods for the AHP. *European Journal of Operational Research*, 145(1), pp.92–108.

Stein, W.E. & Mizzi, P.J., 2007. The harmonic consistency index for the analytic hierarchy process. *European Journal of Operational Research*, 177(1), pp.488–497.

Stillwell, W.G., Winterfeldt, D. von & John, R.S., 1987. Comparing Hierarchical and Nonhierarchical Weighting Methods for Eliciting Multiattribute Value Models. *Management Science*, 33(4), pp.442–450.

Sugden, R., 1985. Why be Consistent? A Critical Analysis of Consistency Requirements in Choice Theory. *Economica*, 52(206), pp.167–183 CR – Copyright © 1985 The London Sch.

Sun, M. & Meng, X., 2009. Taxonomy for change causes and effects in construction projects. *International Journal of Project Management*, 27(6), pp.560–572.

Tatikonda, M.V. & Rosenthal, S.R., 2000. Technology novelty, project complexity, and product development project execution success: a deeper look at task uncertainty in product innovation. *IEEE Transactions on Engineering Management*, 47(1), pp.74–87.

Tavana, M., Kennedy, D., Rappaport, J. & Ugras, J., 1993. An AHP-Delphi Group Decision Support System Applied to Conflict Resolution in Hiring Decisions. *Journal of Management Systems*, 5(1), pp. 49-74.

Temperley, H.N.V., 1982. *Graph Theory and Applications*, Somerset, NJ, USA: John Wiley & Sons.

Thaler, J., 2014. Hubris games: Analyzing success and failure of large-scale energy projects. *Energy Research & Social Science*, 1, pp.238–239.

Thomas, A.B., 2004. *Research Skills for Management Studies*, London: Routledge.

Thomas, J. & Mengel, T., 2008. Preparing project managers to deal with complexity – Advanced project management education. *International Journal of Project*

Management, 26(3), pp.304–315.

Thompson, J.D., 1967. *Organizations in Action*, Berlin: Transaction Publishers.

Treasury board of Canada secretariat, 2009. *Project Complexity and Risk Assessment Tool*, Available at: *http://www.tbs-sct.gc.ca/hgw-cgf/oversight-surveillance/itpm-itgp/pm-gp/doc/pcra-ecrp-eng.asp*

Turner, J.R. & Cochrane, R.A., 1993. Goals-and-methods matrix: coping with projects with ill defined goals and/or methods of achieving them. *International Journal of Project Management*, 11(2), pp.93–102.

Vahdani, B., Karim Jabbari, A., Roshanaei, V. & Zandieh, M., 2010. Extension of the ELECTRE method for decision-making problems with interval weights and data. *The International Journal of Advanced Manufacturing Technology*, 50(5-8), pp.793–800.

Vaidya, O.S. & Kumar, S., 2006. Analytic hierarchy process: An overview of applications. *European Journal of Operational Research*, 169(1), pp.1–29.

Van Marrewijk, A., Clegg, S., Pitsis, T. & Veenswijk, M., 2008. Managing public–private megaprojects: Paradoxes, complexity, and project design. *International Journal of Project Management*, 26(6), pp.591–600.

Van Zolingen, S.J. & Klaassen, C.A., 2003. Selection processes in a Delphi study about key qualifications in Senior Secondary Vocational Education. *Technological Forecasting and Social Change*, 70(4), pp.317–340.

Vargas, L.G., 1997. Comments on Barzilai and Lootsma: Why the Multiplicative AHP Is Invalid: A Practical Counterexample. *Journal of Multi-Criteria Decision Analysis*, 6(3), pp.169–170.

Vidal, L.-A., 2009. *Thinking Project Management in the Age of Complexity*. École Centrale Des Arts Et Manufactures.

Vidal, L.-A. & Marle, F., 2008. Understanding project complexity: implications on project management. *Kybernetes*, 37(8), pp.1094–1110.

Vidal, L.-A., Marle, F. & Bocquet, J.-C., 2011. Measuring project complexity using the Analytic Hierarchy Process. *International Journal of Project Management*, 29(6), pp.718–727.

Vincke, J. & Brans, J.P., 1985. A preference ranking organization method. The PROMETHEE method for MCDM. *Management Science*, 31, pp.641–656.

Wang, Y.-M. & Elhag, T.M.S., 2006. An approach to avoiding rank reversal in AHP. *Decision Support Systems*, 42(3), pp.1474–1480.

Weaver, W., 1948. Science and Complexity. *American Scientist*, 36, pp.536–547.

Weber, M., Eisenführ, F. & von Winterfeldt, D., 1988. The Effects of Splitting Attributes on Weights in Multiattribute Utility Measurement. *Management Science*, 34(4), pp.431–445.

Whitty, S.J. & Maylor, H., 2009. And then came Complex Project Management (revised). *International Journal of Project Management*, 27(3), pp.304–310.

Williams, T., 2005. Assessing and Moving on From the Dominant Project Management Discourse in the Light of Project Overruns. *IEEE Transactions on Engineering Management*, 52(4), pp.497–508.

Williams, T., 2013. *MEGAPROJECTS: Shaping the Research Agenda Symposium Record*, COST Megaprojects, Available at: *http://www.mega-project.eu/assets/exp/resources/Symposium_record_final.docx*

Williams, T., 1999. The need for new paradigms for complex projects. *International Journal of Project Management*, 17(5), pp.269–273.

Williams, T., 2002. *Modelling Complex Projects*, London: John Wiley & Sons.

Wood, H.L. & Ashton, P., 2010. The Factors of Project Complexity. In *CIB World Building Congress, , Salford, UK.*

World Bank, 2009. *Publishing Information on Public Construction Projects*, Available at: *https://openknowledge.worldbank.org/bitstream/handle/10986/3734/WPS5247.txt?sequence=2&isAllowed=y*

Worren, N., 2012. *Organisation Design: Re-Defining Complex Systems*, Pearson.

Xia, B. & Chan, A.P.C., 2012. Measuring complexity for building projects: a Delphi study. *Engineering, Construction and Architectural Management*, 19(1), pp.7–24.

Xia, W. & Lee, G., 2004. Grasping the complexity of IS development projects. *Communications of the ACM*, 47(5), pp.68–74.

Xia, W.D. & Lee, G.H., 2005. Complexity of information systems development projects: Conceptualization and measurement development. *Journal of Management Information Systems*, 22(1), pp.45–83.

Yin, R.K., 2009. *Case Study Research: Design and Methods (Applied Social Research Methods)*, London: SAGE Publications.

Yoon, K.P. & Hwang, C., 1995. *Multiple Attribute Decision Making: An Introduction*, London: SAGE Publications.

Yue, Z., 2012. Approach to group decision making based on determining the weights of experts by using projection method. *Applied Mathematical Modelling*, 36(7), pp.2900–2910.

Zanakis, S.H., Solomonb, A., Wisharta, N. & Dublish S., 1998. Multi-attribute decision making: A simulation comparison of select methods. *European Journal of Operational Research*, 107(3), pp.507–529.

Zhang, H., Dong, Y. & Xu, Y., 2014. An Analysis of Several Novel Frameworks and Models in the Consensus Reaching Process. *Procedia Computer Science*, 31, pp.245–254.

Appendix 1: Invitation to participate in Delphi research

Centre of Excellence in Sustainable Building Design

My name is Ehsan Kian and I am a PhD candidate in construction management at the school of Built Environment, Heriot-Watt University, Edinburgh, UK. Also I am an associate member of EU COST action TU1003 Megaprojects since 2012. A copy of my professional profile is attached to this letter on attachment 1. My PhD research is entitled "Development of a project complexity assessment framework in energy megaprojects". A brief overview of the project is presented in attachment 1, with research background and summary of works that have conducted.

A megaproject is characterised by its large size of investment, long project duration and high technical and process complexities. Megaprojects in the energy sector might include nuclear power plant construction, oil exploration and wind farm installation. There is strong evidence that this type of projects often experience problems in practice, partly due to the increased complexity and the lack of appropriate tools to evaluate and manage that complexity. My research aims to fill this gap by developing a new framework for assessing project complexity, which can assist decision-makers and practitioners to analyse the complexity of energy megaprojects.

At the first step, I have systematically reviewed and synthesised literature on project complexity and energy megaprojects, and developed a project complexity taxonomy, which consists of a comprehensive list of 51 indicators. These indicators are divided into two main groups: external and internal, each group is further divided into two and three levels respectively.

My next task is to determine the appropriate weights for different indicators and specify the assessment method for each of them. I am writing to invite you to participate in an expert panel to help me complete this important task. As an expert panel member, I need you to complete a questionnaire in two different rounds. It is done through email and does not require any face-to-face discussion. Each round should not take more than 30 minutes of your time. The participation of experts like you is crucial to the success of my research. Your assistance will be highly appreciated.

The research is conducted following Heriot-Watt University's ethical guidelines and respects the privacy and anonymity of all participants. The results of this study will be available to all participating experts.

If you agree to participate in this Delphi research, please fill the round 1 questionnaire in attachment 2 and send it back to Ek118@hw.ac.uk within one week from the time of receiving this email. If you are not able to participate in this research, you may know somebody else who could, in which case I would very much appreciate if you could provide me with their contact details.

Do not hesitate to contact me, should you have any questions regarding the research.

Yours sincerely

Ehsan Kian Manesh Rad

Researcher profile

- PhD Candidate Construction Management, "Development of a project complexity assessment method for energy megaprojects", Heriot-Watt Uni., 2011-2015.
- Teaching assistant at HWU
- MEng Industrial engineering, 2011, Universidad Politecnica de Madrid, Spain
- BEng Industrial engineering, 2002, Iran

- Multifaceted Industrial engineer with more than eight years project management experience in Manufacturing Industry
- PRINCE2 Practitioner
- Project Portfolio and Risk management consultant, Expal Aerospace, Spain
- Member of Institute of Industrial Engineers (IIE)
- Associated Member of EU COST action TU1003 of Megaprojects

https://www.linkedin.com/in/ehsankian

Appendix 2: Round 1 Delphi-AHP questionnaire

Development of a project complexity assessment method for energy megaprojects –Delphi study

Round 1

Ehsan Kian

School of the built Environment, Heriot-Watt University, Edinburgh, UK

This Delphi expert panel, of which you are a member, is comprised a number of participants who have been chosen based on their valuable knowledge and experience of megaprojects, in general, and the energy sector in particular. By design, the panel participants will be kept anonymous until the end of the Delphi study to help avoid any bias in experts' judgments and from being influenced by the responses of others. The Delphi study is conducted using questionnaires in two rounds:

- **Round 1**: you are asked to review groups of project complexity indicators using pairwise comparison matrices, where each pair compares two indicators. You are asked to give your judgement on which indicator is the more important of the pair and to what degree.
- **Round 2:** you are provided with the results from round 1 and asked to reconsider your judgment where your original opinion is different from the view of the majority. In addition, you will be asked to review and comment on the scoring methods of complexity indicators.

Instructions

The questionnaire includes 12 matrices which should all be filled. Each matrix consists of a number of indicators. Definitions for each indicator are provided to clarify the meanings of terms of research. Firstly, please fill the first part including a respondent profile and then go through the matrices. Using the nine point ratio scale, the dominance of each indicator over the others is described by allocating the relative scale based on Table 1.

Table 1: Scale of verbal measurement used for this research

Intensity of relative importance	Definition
1	Equally important or preferred
3	Slightly more important or preferred
5	Strongly more important or preferred
7	Very Strongly more important or preferred
9	Extremely more important or preferred
2, 4, 6, 8	Intermediate value

Table 2 presents an example on how to mark subjective preference in pairwise comparison. The intersection of the first line entry (indicator A) and the second column entry (indicator B), the cell marked as “3” meaning that indicator A is “Slightly more important or preferred” than indicator B. Similarly the intersection of the second line entry (indicator B) and the forth column entry (indicator D), the cell marked as “1/5” meaning that indicator D is “Strongly more important or preferred” than indicator B.

Table 2: Example of filling pairwise comparison matrix

	A	**B**	**C**	**D**	**E**
Capital resources (A)		3	5	1	1
Disciplines (B)			5	1/5	1
People (C)				7	3
Physical resources (D)					1/3
Information (E)					

Once you have completed the questionnaire please email it to ***EK118@HW.AC.UK***.

Questionnaire:

1. **Respondent Profile (All questions answer is required)**

1.4 What is your region of work?

☐EU

☐Non-EU

1.5 How many years of experience do you have?

☐<5

☐6-10

☐11-15

☐16-20

☐>20

1.6 What is your professional sector?

☐Oil & Gas

☐Renewable

☐Utility

☐Consultancy

☐Construction

☐Contractors

☐Other (Please specify):

………………………………………………………………………………………

1.7 Rank your knowledge and experience level in general megaprojects, and in the energy sector in particular, using the following guidelines:
(Please tick inside the cell below your desired answer)

	Familiar	**Knowledgeable**	**Advanced**	**Expert**
Megaprojects	☐	☐	☐	☐
Energy	☐	☐	☐	☐

Familiar	**You have general knowledge about the topic, but not practically applied it.**
Knowledgeable	You feel you have a proficient level of knowledge about the topic. You have read about the topic and formed some opinions about it.
Advanced	You were once an expert, but feel somewhat rusty now, or are in the process of becoming an expert but still have some way to go to achieve mastery of the topic, or if you work in a neighbouring field and occasionally draw upon or contribute to the development of the topic.
Expert	You consider yourself to belong to the community of people who currently dedicate themselves to the topic matter, and are recognised outside of your organisation as having a strong grasp of trends or other aspects of the topic.

2. Pairwise comparison matrices

Please compare and highlight the preferred complexity indicator(s) in terms of importance in energy or megaprojects' context and according to the guides and examples described in Tables 1 and 2. Also, note that a definition of each indicator is provided after the corresponding matrix.

a) Matrix 1

	A	B	C	D	E	F	G	H	I	J

Changing economy (A)										
Market competition (B)										
Market unpredictability (C)										
Stability of project environment (D)										
Interaction between the technology system and external environment (E)										
Local laws and regulations (F)										
Political influence (G)										
Cultural configuration (H)										
Cultural differences (I)										
Significance on public agenda (J)										

- **Changing economy:** Changes and fluctuations in economic situations of country or internationally.
- **Market competition:** Level of competition between competitors in market.
- **Market unpredictability:** The degree that market demand and supply are not certain.
- **Stability of project environment:** The level of stability and strength of the projects' external environment during the execution of the project
- **Interaction between the technology system and external environment:** The level of interaction between technological aspects of a project and the external environment.
- **Local laws and regulations:** Regulations in external environment of project e.g. national or international laws.
- **Political influence:** Effects imposed to project from political situations.
- **Cultural configuration:** During project operation, external stakeholders should interact and engage with project respecting to cultural notion and structure of the project.
- **Cultural differences:** Differences between cultural features of external stakeholders.
- **Significance on public agenda:** Importance of project from the public interest and point of view.

---

b) Matrix 2

	A	B	C	D	E	F	G	H	I	J
Capital resources (A)										
Disciplines (B)										

People (C)										
Physical resources (D)										
Information (E)										
Tasks (F)										
Time (G)										
Tools & methods (H)										
Objectives (I)										
Technical (J)										

- **Capital resources:** Fund and finance, investing and monetary requirements of projects.
- **Disciplines:** Standards and methods within the project organisation.
- **People**: Human resources engaged in the project environment.
- **Physical resources**: Matters regarding machinery, infrastructures and goods which are imperative for project execution.
- **Information**: Information and its systems as a part of the project organisation environmental required to execute projects successfully whether in the primary stage or during the operation phase.
- **Tasks:** Activities and tasks which are needed or under progress to deliver the project
- **Time:** Length of project, schedule and planning.
- **Tools and Methods**: Methods to manage the project mostly tools and techniques that enable the project team to establish their work to meet constraints and achieve the goals.
- **Objectives:** Project goals and objectives which should be achieved through the project execution.
- **Technical:** Technical aspects of a project, from technology and innovation sides.

---

c) Matrix 3

	A	B
Extent of capital investment (A)		
Variety of investors and financial resources (B)		

- **Extent of capital investment:** Size of project in term of capital investment and funding.
- **Variety of investors and financial resources:** level of variation between main project investors and resources.

---

d) Matrix 4

	A	B	C	D
Contract types (A)				
Variety of institutional configuration (B)				
Support from permanent organisation (C)				
Team cooperation and communication (D)				

- **Contract types:** The range of different types of contracts that are or will be applied in the project.
- **Variety of institutional configuration:** The level of variation in the institutional structure of project organisation in terms of hierarchical levels, norms, standards and disciplines.
- **Support from permanent organisation:** The level of support from the permanent organisation which owns the project.
- **Team cooperation and communication:** The level of cooperation and communication between project team.

---

e) Matrix 5

	A	B	C	D	E	F
Availability of human resources (A)						
Level of trust (inter/intra teams) (B)						
Diversity of participants (C)						
Dynamic and evolving team structure (D)						
Experience and capabilities within teams (E)						
Interest and perspectives among stakeholders (F)						

- **Availability of human resources:** Availability of human resources which are due to sharing.
- **Level of trust (inter/intra teams):** The level of trust between project team and related project contractors.
- **Diversity of participants:** The level of diversity among participants in a project. E.g. Number of teams or different nationalities.
- **Dynamic and evolving team structure**: Dynamism and evolution in the structure of teams.

- **Experience and capabilities within teams:** The level of experience within the project teams and capabilities which are needed to effectively deliver the project.
- **Interest and perspectives among stakeholders:** Differences and diversities between interests of project stakeholders.

---

f) Matrix 6

	A	B	C
Resource and raw material interdependencies (A)			
Variety of resources (B)			
Availability of physical resources (C)			

- **Resource and raw material interdependencies:** Level of interrelation among the physical resources are due to sharing.
- **Variety of resources:** The level of variation between resources which are deploying in the project.
- **Availability of physical resources:** The level of availability of physical resources.

---

g) Matrix 7

	A	B	C	D
Availability of information (A)				
Reliability of information platforms (B)				
Interdependence of information systems (C)				
Level of processing and transferring information (D)				

- **Availability of information:** The level of availability of information in primary or operation stages of the project.
- **Reliability of information platforms:** The degree of reliability of information systems/platforms within the project.
- **Interdependence of information systems:** Interrelations between information systems/platforms
- **Level of processing and transferring information:** The level of intensity of activities for processing and transferring information in the project.

---

h) Matrix 8

	A	B	C	D	E	F

Diversity of sites and locations (A)						
Process interdependencies (B)						
Dependencies between tasks (C)						
Number of activities (D)						
Unpredictability of tasks (E)						
Diversity of activities elements (F)						

- **Diversity of sites and locations:** The extent of usage of different sites and location in the project.
- **Process interdependencies:** The level of interrelation between project processes.
- **Dependencies between tasks:** The level of dependency between project tasks.
- **Number of activities:** The extent of tasks and decisions which should be taken to achieve the project's goals.
- **Unpredictability of tasks:** The level which tasks are unpredictable to achieve their goals.
- **Diversity of activities elements:** The degree of diversity between elements of tasks or decision.

---

i) Matrix 9

	A	B	C
Duration of project (A)			
Dependencies between schedules (B)			
Intensity of project schedule (C)			

- **Duration of project:** The total length of project.
- **Dependencies between schedules:** The level of interrelation and dependency between the project schedules.
- **Intensity of project schedule:** The degree of which project schedule is under pressure or urgency.

---

j) Matrix 10

	A	B
Applicability of project management methods and tools (A)		
Variety of project management methods and tools (B)		

- **Applicability of Project Management (PM) methods and tools:** The degree which PM tools and methods can be effectively applied in the project.
- **Variety of project management methods and tools:** The extent which different PM tools are applied in the project.

---

k) Matrix 11

	A	B	C	D
Diversity of goals and objectives (A)				
Interdependence of objectives (B)				
Transparency of Objectives (C)				
Scope changing (D)				

- **Diversity of goals and objectives:** the level of diversity between goals and objectives of the project.
- **Interdependence of objectives:** The degree of interrelation between the project objectives.
- **Transparency of objectives:** The level of transparency and clarity of the project goals.
- **Scope changing:** The extent to which the scope of the project might change during the project's execution.

---

l) Matrix 12

	A	B	C	D	E	F	G
Level of innovation (A)							
Technological experience and capabilities (B)							
Repetitiveness of process (C)							
Specifications interdependencies (D)							
Technological varieties (E)							
Variety of system components (F)							
Changing technology (G)							

- **Level of innovation:** The level of innovation which exists or is needed in the project in terms of creativity, organisational and technological novelty.
- **Technological experience and capabilities:** The extent which technological experience and capabilities are needed to achieve project goals.
- **Repetitiveness of process:** The level at which processes from previous analogous project are possible to repeat and apply in the project.

- **Specifications interdependencies:** The level of interrelation between project specifications or final product features.
- **Technological varieties:** The degree of technological diversity within the project in terms of process or different technologies.
- **Variety of system components:** The level of variation among components in the project system.
- **Changing technology:** the degree of change of technology during project life cycle.

Appendix 3: Round 2 Delphi-AHP questionnaire

Centre of Excellence in Sustainable Building Design

Dear ….

Thank you very much for taking part in the first round of the Delphi study in July. You are among a number of excellent experts from around the world who kindly and enthusiastically contributed to this research. Your judgements have been a very precious input for this part of my study on defining and prioritising the project complexity indicators in energy megaprojects. Your pairwise comparison marks now have been analysed in conjunction with those of other experts of the panel. As you are aware, the aim of Delphi study process is to reach the highest level of consensus between the experts on a particular judgment. For this reason, a second round of Delphi is needed for this study.

The process of filling the questionnaire in the second round is different from round 1. You are only asked to reconsider some of your initial judgments, where your score was different from the majority judgement. The detailed instruction and pairwise comparison matrices are provided in attachment 1.

It is highly appreciated if you could complete and email the questionnaire within one week from the time of receiving this email to EK118@HW.AC.UK. Your contribution in this round is vital to the completion of this stage of my research. I will provide you with the results of the final analysis.

Do not hesitate to contact me, should you have any question regarding the research.

Yours sincerely

Ehsan Kian Manesh Rad

Development of a Project Complexity Assessment method for Energy Megaprojects –Delphi Study

Round 2

Ehsan Kian

School of the Built Environment, Heriot-Watt University, Edinburgh, UK

Please note that this is the second and final round of this Delphi study. As described before, in this round experts will be provided with the results from round 1 and asked to reconsider some of their judgments where the original opinion is different from the view of the majority. The aim of this process is to attain the highest level of consensus among experts in a panel.

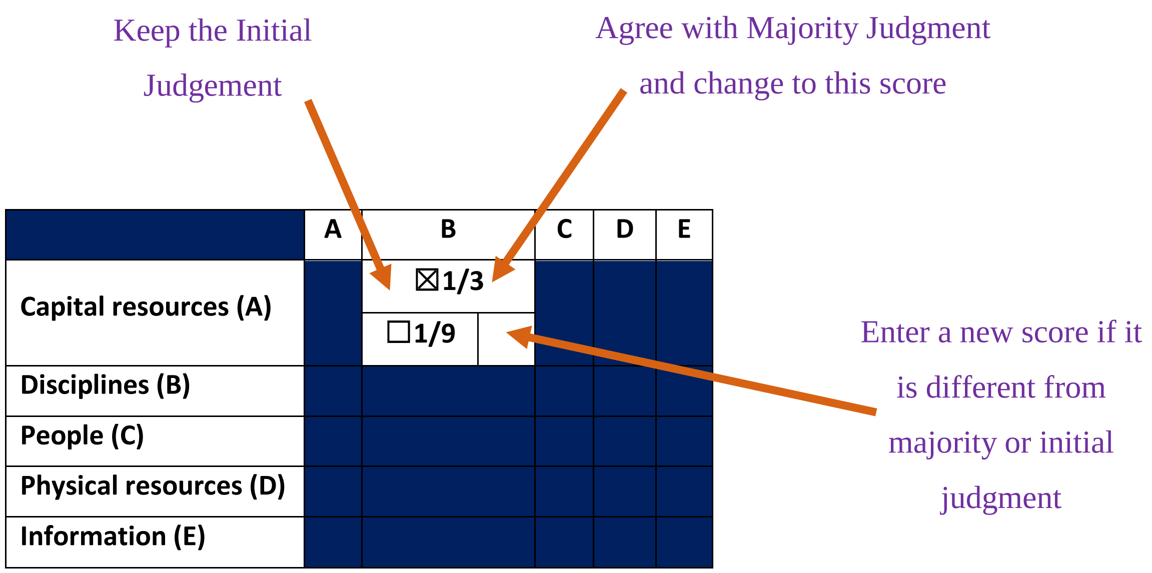
Instructions

In this round, you might only be provided with some of the questionnaire which you answered in first round. Similar to the first round, each matrix consists of a number of indicators. Definition for each indicator is provided to clarify the meanings of terms in research. Using the nine point ratio scale, the dominance of each indicator over the others is described by allocating the relative scale based on the Table 1.

Table 1: Scale of verbal measurement used for this research

Intensity of relative importance	Definition
1	Equally important or preferred
3	Slightly more important or preferred
5	Strongly more important or preferred
7	Very Strongly more important or preferred
9	Extremely more important or preferred
2, 4, 6, 8	Intermediate value

Table 2 presents an example on how to score subjective preference in pairwise comparison in round 2. Different from the first round, some of the cells are dark coloured which means you do not need to make any change for those comparisons. One or more of the cells are open to fill in some matrices. These cells divided into 3 parts; the upper part shows the **majority judgment** comparison score between two indicators, the lower part which is divided to two spaces, the first number on the left shows **your initial judgment in round 1** and the empty part on the right, gives you the choice to enter a **new score** for your judgment. For the choice of agreeing with the majority judgment or keeping the initial value, you can easily tick the box on the left side of number. As an example in table 2, only intersection cell between the first line entry (indicator A) and the second column entry (indicator B) is available to changes and the rest of the cells are dark coloured. The upper number scored as “1/3” presents that majority of experts declared indicator B is “Slightly more important or preferred” than indicator A. The lower left number marked “1/9” is the initial judgment of an expert means that indicator B “Extremely more important or preferred” than indicator A. The expert has decided to change the initial judgment and ticked the box on the upper space means he/she agreed to update his/her judgment to the majority score.



Pairwise comparison matrices for round 2 (an instance sent to expert X)

Please compare and highlight the preferred complexity indicator(s) in terms of importance in energy or megaprojects context and according to the guides and examples described in Tables 1 and 2. Also, note that definition of each indicator is provided after the corresponding matrix.

m) Matrix 1

	A	B	C	D	E	F	G	H	I	J
Changing economy (A)										
Market competition (B)										
Market unpredictability (C)										
Stability of project environment (D)										
Interaction between the technology system and external environment (E)										
Local laws and regulations (F)										
Political influence (G)										
Cultural configuration (H)										
Cultural differences (I)										
Significance on public agenda (J)										

---

n) Matrix 2

	A	B	C	D	E	F	G	H	I	J
Capital resources (A)										
Disciplines (B)							☐2 ☐1/7		☐3 ☐1/7	
People (C)										
Physical resources (D)										
Information (E)										
Tasks (F)										
Time (G)										
Tools & methods (H)										
Objectives (I)										
Technical (J)										

- **Disciplines:** Standards and methods within the project organisation.
- **Time:** Length of project, schedule and planning.

- **Objectives:** Project goals and objectives which should be achieved through the project execution.

o) Matrix 3

	A	B
Extent of capital investment (A)		☐3 ☐ 5
Variety of investors and financial resources (B)		

- **Extent of capital investment:** Size of project in term of capital investment and funding.
- **Variety of investors and financial resources:** level of variation between main project investors and resources.

p) Matrix 4

	A	B	C	D
Contract types (A)				
Variety of institutional configuration (B)				
Support from permanent organisation (C)				
Team cooperation and communication (D)				

q) Matrix 5

	A	B	C	D	E	F
Availability of human resources (A)		☐1/3 ☐5	☐3 ☐ 7			
Level of trust (inter/intra teams) (B)						
Diversity of participants (C)						
Dynamic and evolving team structure (D)						
Experience and capabilities within teams (E)						
Interest and perspectives among stakeholders (F)						

- **Availability of human resources:** Availability of human resources which are due to sharing.

- **Level of trust (inter/intra teams):** The level of trust between project team and related project contractors.
- **Diversity of participants:** The level of diversity among participants in a project. E.g. Number of teams or different nationalities.

---

r) Matrix 6

	A	B	C
Resource and raw material interdependencies (A)			
Variety of resources (B)			
Availability of physical resources (C)			

---

s) Matrix 7

	A	B	C	D
Availability of information (A)				
Reliability of information platforms (B)				☐5 ☐1
Interdependence of information systems (C)				
Level of processing and transferring information (D)				

- **Reliability of information platforms:** The degree of reliability of information systems/platforms within the project.
- **Level of processing and transferring information:** The level of intensity of activities for processing and transferring information in the project.

---

t) Matrix 8

	A	B	C	D	E	F
Diversity of sites and locations (A)						
Process interdependencies (B)						
Dependencies between tasks (C)						
Number of activities (D)						
Unpredictability of tasks (E)						
Diversity of activities elements (F)						

---

u) Matrix 9

	A	B	C
Duration of project (A)			

Dependencies between schedules (B)			
Intensity of project schedule (C)			

---

v) Matrix 10

	A	B
Applicability of project management methods and tools (A)		
Variety of project management methods and tools (B)		

---

w) Matrix 11

	A	B	C	D
Diversity of goals and objectives (A)				
Interdependence of objectives (B)			☐1/5 ☐1/2	
Transparency of Objectives (C)				☐1 ☐3
Scope changing (D)				

- **Interdependence of objectives:** The degree of interrelation between the project objectives.
- **Transparency of Objectives:** The level of transparency and clarity of the project goals.
- **Scope changing:** The extent which scope of project might change during the project execution.

---

x) Matrix 12

	A	B	C	D	E	F	G
Level of innovation (A)						☐5 ☐ 1/2	
Technological experience and capabilities (B)							
Repetitiveness of process (C)					☐1/5 ☐5		
Specifications interdependencies (D)							
Technological varieties (E)							☐1/3

							☐ 2	
Variety of system components (F)								
Changing technology (G)								

- **Level of innovation:** The level of innovation which exists or is needed in the project in terms of creativity, organisational and technological novelty.
- **Repetitiveness of process:** The level, which processes from previous analogous project are possible to repeat and apply in the project.
- **Specifications interdependencies:** The level of interrelation between project specifications or final product features.
- **Variety of system components:** The level of variation among components in the project system.

Changing technology: the degree of change of technology during a project's life cycle.

Appendix 4: Detailed results of round 1 Delphi-AHP – Consistency-checking

Expert	cd^1	R^1	N cd^1	cd^2	R^2	N cd^2	cd^3	cd^4	R^4	N cd^4	cd^5	R^5	N cd^5	cd^6	R^6	N cd^6	cd^7	R^7	N cd^7	cd^8	R^8	N cd^8	cd^9	R^9	N cd^9	cd^{10}	cd^{11}	R^{11}	N cd^{11}	cd^{12}	R^{12}	N cd^{12}	cd^l avg.	R^l avg.	BC avg.
	M1			M2			M3	M4			M5			M6			M7			M8			M9			M10	M11			M12					
L1	89.72%	15.00%	91.12%	88.06%	25.00%	90.19%	-	93.75%	0.00%	93.75%	91.67%	0.00%	91.67%	99.94%	0.00%	99.94%	93.39%	0.00%	93.39%	87.29%	26.67%	90.83%	93.66%	0.00%	93.66%	-	84.17%	33.33%	99.49%	86.13%	33.33%	91.07%	90.78%	13.33%	93.51%
L2	90.90%	0.00%	90.90%	89.69%	10.00%	90.61%	-	89.58%	16.67%	95.83%	92.08%	0.00%	92.08%	99.81%	0.00%	99.81%	93.70%	0.00%	93.70%	91.04%	0.00%	91.04%	98.86%	0.00%	98.86%	-	91.74%	0.00%	91.74%	93.45%	0.00%	93.45%	93.09%	1.00%	93.80%
L3	92.15%	0.00%	92.15%	91.70%	0.00%	91.70%	-	93.75%	0.00%	93.75%	91.67%	0.00%	91.67%	87.94%	33.33%	91.16%	74.95%	83.33%	91.51%	93.75%	0.00%	93.75%	62.59%	66.67%	90.09%	-	89.57%	33.33%	92.95%	89.05%	9.52%	91.45%	86.71%	22.62%	92.02%
L4	89.06%	12.50%	90.01%	87.26%	15.00%	90.10%	-	91.67%	0.00%	91.67%	87.91%	20.00%	91.52%	93.75%	0.00%	93.75%	91.65%	0.00%	91.65%	91.04%	0.00%	91.04%	93.84%	0.00%	93.84%	-	62.44%	66.67%	91.16%	91.37%	0.00%	91.37%	88.00%	11.42%	91.61%
L5	91.25%	0.00%	91.25%	91.04%	0.00%	91.04%	-	100.00%	0.00%	100.00%	89.79%	6.67%	90.58%	99.81%	0.00%	99.81%	89.49%	33.33%	94.89%	96.04%	0.00%	96.04%	99.59%	0.00%	99.59%	-	94.79%	0.00%	94.79%	93.63%	0.00%	93.63%	94.54%	4.00%	95.16%
L6	88.75%	10.00%	91.13%	91.81%	0.00%	91.81%	-	87.50%	16.67%	95.00%	95.83%	0.00%	95.83%	100.00%	0.00%	100.00%	87.41%	16.67%	94.91%	100.00%	0.00%	100.00%	87.59%	33.33%	90.00%	-	72.90%	50.00%	91.78%	90.48%	0.00%	90.48%	90.23%	11.00%	94.09%
L7	89.85%	10.00%	90.83%	90.53%	0.00%	90.53%	-	90.51%	0.00%	90.51%	87.32%	26.67%	92.33%	96.15%	0.00%	96.15%	88.34%	16.67%	93.21%	97.64%	0.00%	97.64%	92.84%	0.00%	92.84%	-	86.63%	33.33%	90.36%	91.09%	0.00%	91.09%	91.09%	8.67%	92.55%
L8	91.79%	0.00%	91.79%	90.59%	0.00%	90.59%	-	88.67%	16.67%	91.55%	89.74%	13.33%	90.25%	95.43%	0.00%	95.43%	89.62%	16.67%	94.89%	89.13%	33.33%	94.69%	78.50%	66.67%	92.75%	-	74.94%	50.00%	91.88%	96.73%	0.00%	96.73%	88.51%	18.00%	93.06%
L9	90.89%	0.00%	90.89%	90.79%	0.00%	90.79%	-	97.49%	0.00%	97.49%	91.67%	0.00%	91.67%	96.48%	0.00%	96.48%	94.53%	0.00%	94.53%	91.44%	0.00%	91.44%	97.84%	0.00%	97.84%	-	93.49%	0.00%	93.49%	87.16%	38.10%	92.31%	93.18%	3.81%	93.69%
L10	88.89%	15.00%	91.14%	89.84%	20.00%	92.55%	-	92.53%	0.00%	92.53%	88.24%	26.67%	91.87%	88.04%	33.33%	91.97%	90.70%	0.00%	90.70%	96.12%	0.00%	96.12%	94.57%	0.00%	94.57%	-	90.07%	0.00%	90.07%	89.55%	14.29%	90.21%	90.86%	10.93%	92.17%
L11	92.95%	0.00%	92.95%	91.25%	0.00%	91.25%	-	92.71%	0.00%	92.71%	90.83%	0.00%	90.83%	93.75%	0.00%	93.75%	89.58%	16.67%	93.96%	92.92%	0.00%	92.92%	93.75%	0.00%	93.75%	-	88.54%	33.33%	93.44%	92.86%	0.00%	92.86%	91.91%	5.00%	92.84%

AVG	L20	L19	L18	L17	L16	L15	L14	L13	L12
90.33%	87.32%	91.79%	90.06%	93.87%	92.34%	88.92%	91.62%	87.99%	86.53%
8.38%	22.50%	0.00%	0.00%	0.00%	0.00%	12.50%	0.00%	37.50%	32.50%
91.51%	93.26%	91.79%	90.06%	93.87%	92.34%	90.90%	91.62%	91.34%	90.92%
90.45%	89.86%	90.29%	91.41%	86.22%	93.22%	90.55%	90.51%	91.52%	92.81%
6.38%	22.50%	0.00%	0.00%	35.00%	0.00%	0.00%	0.00%	0.00%	0.00%
91.35%	93.44%	90.29%	91.41%	92.11%	93.22%	90.55%	90.51%	91.52%	92.81%
0.00%	-	-	-	-	-	-	-	-	-
91.82%	94.51%	90.68%	91.43%	88.43%	89.80%	87.20%	90.69%	95.86%	89.58%
6.67%	0.00%	0.00%	0.00%	16.67%	16.67%	33.33%	0.00%	0.00%	16.67%
93.28%	94.51%	90.68%	91.43%	91.47%	93.70%	92.39%	90.69%	95.86%	90.00%
90.79%	94.12%	87.71%	95.16%	86.00%	92.60%	93.36%	91.66%	85.27%	93.12%
10.33%	0.00%	26.67%	0.00%	46.67%	0.00%	0.00%	0.00%	40.00%	0.00%
92.24%	94.12%	92.54%	95.16%	90.32%	92.60%	93.36%	91.66%	91.54%	93.12%
94.50%	85.03%	99.51%	92.74%	87.37%	99.78%	97.29%	93.83%	89.53%	93.75%
10.00%	66.67%	0.00%	0.00%	33.33%	0.00%	0.00%	0.00%	33.33%	0.00%
95.75%	93.28%	99.51%	92.74%	92.37%	99.78%	97.29%	93.83%	94.12%	93.75%
89.12%	89.41%	91.90%	86.49%	95.31%	84.64%	87.76%	94.23%	85.54%	83.78%
16.67%	16.67%	0.00%	16.67%	0.00%	50.00%	16.67%	0.00%	16.67%	33.33%
93.25%	94.59%	91.90%	92.71%	95.31%	91.56%	93.02%	94.23%	92.58%	91.74%
92.15%	94.78%	90.54%	91.87%	88.57%	91.61%	90.30%	89.14%	91.29%	88.54%
6.33%	0.00%	0.00%	0.00%	26.67%	0.00%	0.00%	20.00%	0.00%	20.00%
93.05%	94.78%	90.54%	91.87%	92.10%	91.61%	90.30%	92.51%	91.29%	90.44%
92.06%	91.44%	93.15%	97.99%	87.91%	88.91%	97.73%	96.57%	94.01%	99.81%
11.67%	0.00%	0.00%	0.00%	33.33%	33.33%	0.00%	0.00%	0.00%	0.00%
94.61%	91.44%	93.15%	97.99%	90.21%	93.55%	97.73%	96.57%	94.01%	99.81%
-	-	-	-	-	-	-	-	-	-
86.73%	96.94%	86.64%	90.68%	89.57%	86.52%	92.56%	91.12%	82.71%	88.59%
24.17%	0.00%	50.00%	0.00%	16.67%	33.33%	0.00%	0.00%	50.00%	33.33%
92.86%	96.94%	94.63%	90.68%	91.06%	92.90%	92.56%	91.12%	91.79%	94.29%
91.37%	97.28%	91.74%	92.77%	89.76%	96.72%	90.74%	86.68%	93.59%	86.55%
7.86%	0.00%	0.00%	0.00%	14.29%	0.00%	0.00%	28.57%	0.00%	19.05%
92.49%	97.28%	91.74%	92.77%	90.81%	96.72%	90.74%	90.01%	93.59%	91.43%
90.93%	92.07%	91.40%	92.06%	89.30%	91.61%	91.64%	91.61%	89.73%	90.31%
10.18%	12.83%	7.67%	1.67%	20.60%	11.67%	2.92%	4.86%	17.75%	13.82%
93.04%	94.36%	92.68%	92.68%	91.96%	93.80%	92.88%	92.28%	92.76%	92.83%

Appendix 5: Detailed results of round 2 Delphi-AHP – Consensus-building

Matrices	Professionals				Academics				Total			
	cr	R	Accepted R	N *cr*	*cr*	R	Accepted R	N *cr*	*cr*	R	Accepted R	N *cr*
M1	79.79%	11.11%	8.67%	82.71%	72.93%	20.55%	16.67%	78.38%	76.36%	15.83%	12.67%	**80.54%**
M2	83.03%	9.22%	5.89%	84.22%	74.59%	23.33%	14.44%	77.63%	78.81%	16.28%	10.16%	**80.93%**
M3	74.54%	35.00%	25.00%	81.36%	71.45%	45.00%	35.00%	80.34%	73.00%	40.00%	30.00%	**80.85%**
M4	70.87%	20.83%	15.83%	84.95%	73.32%	15.00%	11.66%	83.40%	72.10%	17.92%	13.75%	**84.17%**
M5	82.96%	15.66%	9.67%	85.12%	80.87%	14.33%	8.67%	82.81%	81.92%	15.00%	9.17%	**83.96%**
M6	66.43%	36.66%	28.33%	73.52%	61.79%	43.33%	36.67%	70.96%	64.11%	40.00%	32.50%	**72.24%**
M7	85.48%	0.00%	0.00%	85.48%	80.36%	15.83%	12.50%	86.25%	82.92%	7.92%	6.25%	**85.86%**
M8	72.77%	22.33%	12.33%	75.34%	76.22%	50.00%	29.00%	82.50%	74.49%	36.17%	20.67%	**78.92%**
M9	78.08%	25.00%	18.33%	83.06%	72.74%	33.33%	23.33%	79.18%	75.41%	29.17%	20.83%	**81.12%**
M10	54.78%	45.00%	35.00%	71.14%	52.35%	45.00%	30.00%	65.09%	53.57%	45.00%	32.50%	**71.12%**
M11	78.31%	26.66%	22.50%	84.61%	75.03%	34.16%	28.33%	83.11%	76.67%	30.41%	25.42%	**83.86%**
M12	82.49%	24.28%	19.29%	85.83%	78.25%	30.95%	23.33%	82.44%	80.37%	27.62%	21.31%	**84.13%**
	75.79%	22.65%	16.74%	81.44%	72.49%	30.90%	22.47%	79.34%	74.14%	26.77%	19.60%	**80.39%**

Appendix 6: Expert review spreadsheet questionnaire in INT-Characteristics

Please point out your review and agreement on the measures by clicking only on one of two options: Yes or No. If your answer is No, please present your suggestions in the comment box. You can test the tool, by entering the values of complexity in "Score" column - the defined score are 1, 3 or 5 however 2 and 4 are between values. The results will be presented in "Results CI" sheet. The default values are set at 1 for each indicator.

Category	Indicator	Measure		Score	Review question Do you agree with the defined measure?
Objectives	Variety of goals and objectives	To what level, goals and objectives of the project vary based on the number of contributing criteria? a. There is at least one major private stakeholder exists. b. Government owns at least 50% of project's share c. Environmental activist have opinion and voice about the project d. Local authorities and community have opinion and voice about the project e. Project's owner and client are different f. Project receives a financial support from international sources	1: 0-2 3: 3-4 5: 5-6		☐ Yes ☐ No Comment:

	Interdependence of objectives	What is the level of dependency between the project objectives considering number of criteria are met? a. There are normal dependencies between objectives without or with a low level of uncertainty b. There are symmetric dependencies between objectives (between two correlated objectives, the uncertainty of one objective can only change the probability of reaching to another objective) c. There are asymmetric dependencies between objectives (between two correlated objectives, the uncertainty of one objective leads to changes in stages to achieve another objective e.g. considering change in objectives or scope)	1: a 3: b 5:c		☐ Yes ☐ No Comment:
	Transparency of Objectives	To what extent, project's objectives and delivery requirements are clear, completed, and communicated?	1: All objectives and requirements are clear, complete, and communicated and comparative advantage of project fully understood. 3: Up to 10% of total objectives and requirements are not complete or are undocumented		☐ Yes ☐ No Comment:

			5: More than 10% of total objectives and requirements are not complete or are unclear		
	Scope changing	To what extent project scope is changing or diverging from planned scope or organization's mandate and desired strategic outcomes?	1: The project is fully aligned and it explicitly contributes to the strategic outcomes of the organization or program 3: There is good alignment with the strategic outcome and there is an indirect contribution to the strategic outcomes of the organization or program 5: There is a weak alignment with the strategic outcomes, or scope diverse significantly from		☐ Yes ☐ No Comment:

			planned scope		
Technical	Level of innovation	What is the expected level of innovation within the project? (number of criteria are met). a. High level of technical innovation b. Appearance of relevant new technologies during the project implementation (planning, design, and construction) c. Appearance of relevant (for competitors) new technologies during the project implementation (planning, design, and construction) d. Tendering process favouring innovation e. Using untried technology or materials (not previously used)	1: 0-1 3: 2-3 5: 4-5		☐ Yes ☐ No Comment:
	Technological experience and capabilities	To what extent, technological experience and capabilities within the project are required?	1. Required technologies and experiences are available through similar practiced projects 3. Project is FOAK (First Of A Kind) or unique		☐ Yes ☐ No Comment:

			5. Project is FOAK (First Of A Kind) or unique with high the high level of innovation		
	Repetitiveness of process	Which of the following statements can be adapted in the project?	1.The project can be decomposed in many sub-projects which can fully learn from other similar project 3.The project can be decomposed in some sub-projects and there is a level of learning from other similar projects 5. The project neither effectively can be decomposed in sub-projects nor would be any learning from other similar projects		☐ Yes ☐ No Comment:

	Specifications interdependencies	What is the level of interdependency between the final product specifications based on the following criteria: a. There are normal interdependencies between specifications without or with a low level of uncertainty b. There are symmetric interdependencies between specifications (between two correlated specifications, the uncertainty of producing of one specific can only change probability of the producing to another specific) c. There are asymmetric interdependencies between specifications (between two correlated specifications, the uncertainty of producing one specific leads to changes in producing another specific e.g. redesign or change in quality requirements)	1: a 3: b 5:c		☐ Yes ☐ No Comment:
	Technological varieties	Regarding technological variety of the project, how many of following criteria are met? a. The project requires a high level (greater than normal: average of experienced similar project) of technological availability. b. The project requires technological customization beyond normal configuration c. The project requires a high level of technological performance quality d. The project requires a high level of technological reliability	1: 0-1 3: 2 4: 3-4		☐ Yes ☐ No Comment:

	Variety of system components	Once there is a final product or goal expected from the project, in what extent variety of its components can be described?	1: the final product or goal is mono modular with independent modules 3: the final product or goal is multi modular with independent modules 5: The final product or goal is multi modular with dependent modules		☐ Yes ☐ No Comment:
	Changing technology	What is the level of change in technology before or during the project operation?	1: off the shelf or new integration only 3: Minor modification 5: major modification or substantially new technology		☐ Yes ☐ No Comment:

Appendix 7: Consistency-checking process based on method of Chiclana et al. (2008)

Computation of consistency

In the GDM method with judgments relations, some properties of judgments were articulated by the experts; however, it is necessary to prevent contradictions in their opinions, i.e. inconsistencies. One of these properties is related to the "transitivity" in the pairwise comparison among any three alternatives. In the Chiclana et al. (2008) method, the additive transitivity property is used:

Being $A = (a_{ij})$ a judgment relation, the mathematical formulation for the additive transitivity is suggested as:

$$\left(a_{ij} - 0.5\right) + \left(a_{jk} - 0.5\right) = (a_{ik} - 0.5) \quad \forall\, i, j\,, k\; \in \{\, 1, \dots, n\}. \quad (1$$

Because additive transitivity also indicates additive reciprocity $(a_{ij} + a_{ji} = 1\;\; \forall\, i, j\,)$ the equation (1) can be rewritten as:

$$a_{ik} = \; a_{ij} + \; a_{jk} - 0.5 \;\; \forall\, i, j\,, k\; \in \{\, 1, \dots, n\}. \quad (2$$

Taking into account a reciprocal judgment relation, equation (2) can be used to compute an estimated value of a judgment degree using other judgments degrees. By using an intermediate alternative x_j, the following estimated value of a_{ik} $(\, i\; \neq k)$ is gained:

$$ea_{ik}^{j} = \; a_{ij} + \; a_{jk} - 0.5. \quad (3$$

Then the overall estimated value $ea_{ik}$of a_{ik} is gained as the average of all conceivable values of ea_{ik}^{j} , i.e.,

$$ea_{ik} = \; \sum_{\substack{j=1 \\ j\neq i,k}}^{n} \frac{ea_{ik}^{j}}{n-2} \quad (4$$

The value $|ea_{ik} - \; a_{ik}\,|$ can be used as a measure of the error between a judgment value and its estimated one. The estimated value of $e^2 a_{ik}$ is:

$$e^2 a_{ik} = \; ea_{ik} + \frac{2}{n-2}(a_{ik} - \; ea_{ik}) \quad (5$$

With the aim of normalising the expression domains of the final estimated value of a_{ik} $(\, i\; \neq k)$, ca_{ik}, is determined as the median of the values 0, 1 and ep_{ik}:

$$ca_{ik} = med\{0, 1, ea_{ik}\} \quad (6$$

The error in [0, 1] between a judgment value, a_{ik}, and its final estimated value, ca_{ik}, is:

$$\varepsilon a_{ik} = \; |ca_{ik} - \; a_{ik}| \quad (7$$

As a conclusion, the three stages of consistency checking are proposed as below:

Stage1. Consistency degree related to a pair of alternatives$(x_{i,}, x_k)$,

$$cd_{ik} = 1 - ea_{ik}. \quad (8$$

Stage 2. Consistency degree associated to an alternative $x_{i,}$

$$cd_i = \sum_{\substack{k=1 \\ k \neq i}}^{n} \frac{cd_{ik}}{n-1}. \quad (9$$

The lower cd_i, the less consistent the preference values involving the alternative x_i are with respect to the rest of information.

Stage 3. Consistency degree of the reciprocal judgment relation,

$$cd = \sum_{i=1}^{n} \frac{cd_i}{n} \quad (10$$

The lower cd, the less consistent the reciprocal judgement relation $A = (a_{ij})$ is.

Consistency threshold

Consistency threshold value is identified (β) to classify each expert's preferences as consistent or inconsistent. If all experts satisfy the threshold, i.e. $cd^i \geq \beta$, the process proceeds to the next step, "consensus building system". Otherwise, an automatic consistency building system is applied to:

i. Detect the inconsistent experts, alternatives and judgement values, and
ii. Produce a Substitute consistent judgment value for each one of the inconsistent values.

Saaty (1977) defined 10% as an acceptable level of inconsistency in each matrix, so a consistency threshold value $\beta = 0.9$ is used and each expert judgment relations is assessed against it.

Consistency advice process:

This process advises changes to the experts' judgment values when their consistency degree falls below a specified threshold, using the below three steps:

1) Identify those experts (l) in the panel with a consistency degree cd^l lower than the minimum threshold consistency value (β).
2) Identify for each one experts whose alternatives (i) with a consistency degree (cd_i^l) lower than (β).
3) Identify for each one alternatives the judgment values with a consistency degree (cd_{ij}^l) lower than (β).

The set of preference values to be advised for amendment are

$$\{(l, i, j) \ | max \{cd^l, cd_i^l, cd_{ij}^l\} < \beta \}. \qquad (11$$

The judgment value of the above set (a_{ij}^l) is suggested to be amended to a value closer to its final estimated value (ca_{ij}^l). This amendment makes the original individual judgment relation (A^l) closer to its estimated one (CA^l) and hence it becomes more consistent globally. Therefore, if $cd_{ij}^l < \beta$, in order to obtain the minimum threshold value, (a_{ij}^l) is suggested to be amended to:

$$a_{ij}^{-l} = a_{ij}^l + sign(ca_{ij}^l - a_{ij}^l).(\beta - cd_{ij}^l), \qquad (12$$

Where $sign(X)$ returns the sign of X. Lastly, to maintain reciprocity, the value a_{ji}^l suggested to be amended to $a_{ji}^{-l} = 1 - a_{ij}^{-l}$.

Appendix 8: Consensus- building process based on method of Chiclana et al. (2008)

Computing consensus degrees

The degree of agreement among the experts is calculated based on the distance between their judgment values. The similarity function $s\left(a_{ij}^{r}, a_{ij}^{t}\right) = 1 - \ |a_{ij}^{r} - a_{ij}^{t}\ |$ to measure the similarity of the judgment values of two experts , e_r and e_t, are defined for each pair of alternative, x_i and x_j. Reciprocity of judgments denotes that $\left(a_{ij}^{r}, a_{ij}^{t}\right) = \ s\left(a_{ji}^{r}, a_{ji}^{t}\right)$. The similarity function can be used to determine both consensus degrees and proximity measures. Consensus degrees are computed by combining the similarity of the judgment values of all the experts on each pair of alternatives. Proximity measures are computed by assessing the similarity between the judgments of each expert in the group and the collective judgments.

The calculation of consensus degrees is performed in three steps:

1. For each pair of experts r and *t*, (*r* < *t*), a *similarity matrix* is computed:

$$SM^{rt} = \left(sm_{ij}^{rt}\right) \tag{13}$$

where $sm_{ij}^{rt} = \ s\left(a_{ij}^{r}, a_{ij}^{t}\right) \ \ i, j = 1, \ldots, n \ \wedge i \neq j,$

2. The *consensus matrix* $CM = (cm_{ij})$, is obtained by combining all similarity matrices*:*

$$cm_{ij} = \emptyset\left(sm_{ij}^{rt}\right); r, t = 1, \ldots, m; i, j = 1, \ldots, n \ \wedge r < t \tag{14}$$

The arithmetic mean is used as the combination function $\emptyset$ and $cm_{ij} = \ cm_{ji}$ $(\forall i, j)$.

3. Then three different levels of consensus degrees can be calculated:

Level 1. *Consensus on pairs of alternatives,* ca_{ij}. It assesses the agreement among all experts on the pair of alternatives (x_i, x_j) :

$$ca_{ij} = \ cm_{ij} \ . \tag{15}$$

Level 2. *Consensus on alternatives,* ca_i. It assesses the agreement among all experts on the alternative x_i, and it is determined as the average of the consensus degrees of all the pairs of alternatives relating it:

$$ca_i = \ \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{ca_{ij}}{n-1} \tag{16}$$

Level 3. *Consensus on the relation*, *cr*. It assesses the agreement among all experts for all alternatives, and it is determined as the average of the consensus degrees of all the alternatives:

$$cr = \sum_{i=1}^{n} \frac{ca_i}{n}. \tag{17}$$

The proximity measures are used to determine the experts which are furthest from the group. The first step for this determination is the calculation of the collective judgment relation:

$$A^c = \left(a_{ij}^c\right);\ a_{ij}^c = \psi\left(a_{ij}^1, \ldots, a_{ij}^m\right). \tag{18}$$

As before, the arithmetic mean is used as the combination function ψ.

For each expert, e_t; a proximity matrix is obtained:

$$AM^t = \left(am_{ij}^t\right) \tag{19}$$

with $am_{ij}^t = s(\, a_{ij}^t, a_{ij}^c)$.

Proximity measures can then be calculated for the same three different levels of a judgment relations as above:

Level1. *Proximity on pairs of alternatives*, pa_{ij}^t; which evaluates the proximity between the judgment value of an expert and the conforming collective one on a pair of alternatives (x_i, x_j):

$$pa_{ij}^t = pm_{ij}^t\,. \tag{20}$$

Level2. *Proximity on alternatives*, pa_i^t; which evaluates the proximity between an expert's judgment values of one alternative, x_i against the rest of alternatives and the related collective ones:

$$pa_i^t = \sum_{\substack{j=1 \\ j \neq i}}^{n} \frac{pa_{ij}^t}{n-1} \tag{21}$$

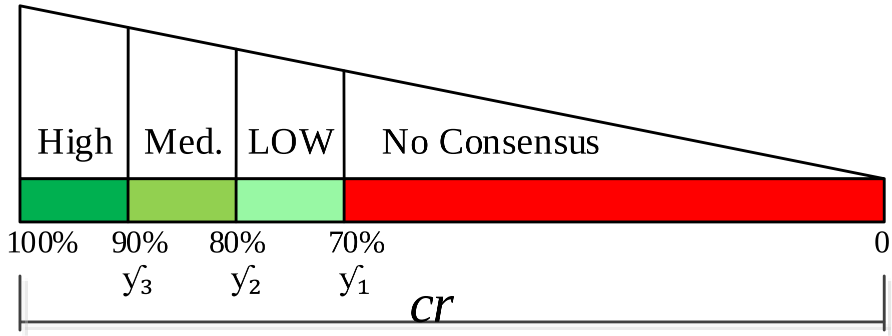
Level3. *Proximity on the relation*, pr^t; which evaluates the global proximity between an expert and the group:

$$pr^t = \sum_{i=1}^{n} \frac{pa_i^t}{n} \tag{22}$$

Consensus threshold

A consensus threshold $\gamma \in [\,0{,}1\,]$ is defined to determine when sufficient consensus is reached ($cr \geq \gamma$), and the final weight aggregation should be carried out to obtain the local weights.

Depending on the type of problem, expert's background, or specific project situations, different levels of consensus may be required. For this reason, three ranges defined by the thresholds γ_1, γ_2 and γ_3 are defined in this research to highlight the consensus rate (cr), as showed in a figure below. The thresholds gauge local consensus (each category) and total consensus and identify if the obtained consensus is acceptable or if the process should progress into another round. In this research, a medium level, i.e. $0.8 \leq cr \leq 0.9$, is considered satisfactory for the total consensus because of the complex character of the problem. The local consensus rates are acceptable if they are within any of γ_1, γ_2 and γ_3 ranges.



Ranges of acceptable consensus

If sufficient consensus is not reached, the process proceeds to an advice stage, which recommend changes to increase the consensus level.

Advice system

This advice process searches for judgment values to be amended by the experts. It first identifies the alternatives with consensus degree less than global consensus level:

$$X_{ch} = \{i|ca_i < cr\} \quad (23$$

Then for each alternatives, judgment values with consensus degree less than global consensus level are identified:

$$P = \{(i,j),(j,i)\big|i \in X_{ch} \wedge ca_{ij} = ca_{ji} < cr\} \quad (24$$

Furthermore, the number of experts needed to modify identified judgments is limited to only those furthest on the identified alternatives. For this purpose, the average of all proximity values on the individual identified alternative is used as the threshold value to nominate the experts that are required to amend judgments. Thus, the set of judgments that each experts e^t should modify is:

$$PREFETCH^t = \{ (i,j)|(i,j) \in P \wedge pa_i^t < \sum_r \frac{pa_i^r}{m} \wedge pa_{ij}^t < \sum_r \frac{pa_{ij}^r}{m}\} \quad (25$$

It is imperative to bring suggestions to the experts to guide them towards an increase of level of consensus. The guide is provided based on the comparison between the individual and combined judgements. The expert e_t is recommended to change a_{ij}^t (and correspondingly a_{ji}^t) by the value $pa_{ij}^t - a_{ij}^c$.

If $a_{ij}^t - a_{ij}^c < 0$, expert e_t will be suggested to increase a_{ij}^t (and decrease a_{ji}^t in the same amount).
If $a_{ij}^t - a_{ij}^c > 0$, expert e_t will be suggested to decrease a_{ij}^t (and increase a_{ji}^t in the same amount).
If $a_{ij}^t - a_{ij}^c = 0$, expert e_t will not be offered any change for a_{ij}^t and a_{ji}^t .